Psychophysiological Correlates of Dynamic Imagery

John Williams, B.Sc.

Submitted for the degree of Doctor of Philosophy to the University of Warwick.

This research was carried out at the Department of Psychology, Warwick and at the

Defence Research Agency, Centre for Human Sciences, Farnborough.

Date of Submission, November 1995

Table of Contents

List of Tables.....iix - x

List of Figures.....xii - xiv

List of Abbreviations.....xv - xv

Acknowledgements.....xvi

Declaration.....xvii

Summary.....ixv

Chapter 1 : Introduction.....1 - 9

1.1 Imaginary Transformation.....2 - 3

1.2 Movement Imagery.....3 - 5

1.3 The Psychophysiological Approach.....5 - 7

1.4 Individual Differences.....7 - 8

1.5 Summary.....8 - 9

Chapter 2 : Dynamic Imagery

- Visual, spatial or motoric representations ?.....10 - 34

2.1 Imaginary Transformation.....11 - 12

2.1.1 The role of motor processes in imaginary transformation.....12 - 1-

2.1.2 The role of visuo-spatial processes in imaginary transformation.....14 - 1:

2.2 Movement imagery.....15 - 3-

2.2.1 The symbolic-perceptual theory of movement imagery.....18 - 2

2.2.2 Movement Imagery - the 'internal and external' view.....21 - 2.

2.2.2.1 Movement Imagery - properties of motor representations.....23 - 2-
2.2.2.2 Movement Imagery - properties of visual representations.....25 - 2
2.2.2.3 Movement Imagery - visual or visuo-spatial representations.....27 - 3
2.3 The functional equivalence of imagery and perception.....31 - 3.
2.4 Conclusion.....34

Chapter 3 : Evidence from Cognitive Neuroscience.....35 - 5

3.1 The hierarchical organisation of the motor system.....36 - 3
3.2 Cortical representations of imaginary transformation.....39 - 44
3.2.1 Effects of brain damage on imaginary transformation.....39 - 4
3.2.2 Psychophysological studies of imaginary transformation.....41 - 4
3.3 Cortical representations of visual imagery.....44 - 52
3.3.1 Effects of brain damage on visual imagery.....44 - 46
3.3.2 Psychophysological studies of visual imagery.....47 - 51
3.4 Cortical representations of movement imagery.....51 - 6(
3.4.1 Effects of brain damage on movement imagery.....51 - 5
3.4.2 Psychophysiological studies of movement imagery.....54 - 5
3.5 Conclusion.....58 - 5

Chapter 4 : Individual Differences in Imagery Ability.....60 - 6

4.1 Assessment of Individual Differences in Imagery Ability.....61 - 6
4.1.1 'Use of imagery' Questionnaires.....61 - 6
4.1.2 Self Report Questionnaires.....62 - 6-
4.1.3 Performance Measures of Imagery Ability.....6 - 6
4.2 The relationship between subjective and objective measures.....65 - 6
4.3 Evidence from psychophysiological studies.....68 - 6
4.4 Conclusion.....6

Chapter 5 : Methodology.....70 - 87

5.1 Regional cerebral blood flow techniques.....70 - 72

5.2 Functional magnetic resonance imaging.....72

5.3 Electrophysiological Techniques.....73 - 74

5.3.1 Electroencephalography.....73

5.3.2 Event Related Potentials.....73

5.4 Apparatus and EEG recording techniques used in this thesis.....74 - 87

5.4.1 The reference electrode.....75

5.4.2 Filtering and digitisation.....76

5.4.3 Artifact removal.....76 - 77

5.4.4 EEG analysis.....77

5.4.5 Quantification of the EEG.....78 - 79

5.4.6 Frequency components of the EEG.....79 - 80

5.4.6.1 Alpha.....80 - 81

5.4.6.2 Beta.....81 - 82

5.4.6.3 The functional significance of alpha and beta.....82 - 83

5.5 Statistical Analysis.....83 - 85

5.5.1 Analysis of Individual Differences.....85 - 87

Chapter 6 : Experiment 1

Does the imaginary transformation of objects in space involve the motor system ?.....88 - 111

6.1 Introduction.....88 - 92

6.1.1 Cortical representations of imaginary transformations.....89 - 90

6.1.2 Individual differences in imagery ability.....90 - 92

6.2 Method.....92 - 94

6.3 Results.....94 - 106

6.3.1 Location of mental rotation effects and correlates of subjective vividness.....95 - 103

6.3.1.1 Behavioural data.....95 - 96

6.3.1.2 Psychophysiological data.....96 - 103

6.3.2 Location of mental rotation effects and correlates of MRT performance.....103 - 106

6.3.2.1 Behavioural data.....103

6.3.2.2 Psychophysiological data.....103 - 106

6.4 Discussion.....106 - 110

6.5 Conclusion.....110 - 111

Chapter 7 : Experiment 2

Does the imagination of bodily movement involve the motor system ?.....112 - 130

7.1 Introduction.....113 - 115

7.2 Method.....115 - 117

7.3 Results.....117

7.3.1 Behavioural data.....117

7.3.2 Psychophysiological data.....118 - 121

7.3.2.1 Location of imagery effects and correlates of subjective vividness.....122 - 124

7.3.2.2 Location of imagery effects and correlates of MRT performance.....124 - 130

7.4 Discussion.....130 - 131

Chapter 8: Experiments 3 & 4

Are overt actions and movement imagery functionally equivalent ?...131 - 197

8.1 **Experiment 3**.....137 - 171

8.1.1 Introduction.....133 - 138

8.1.2 Method.....138 - 142

8.1.3 Results.....142 - 167

8.1.3.1 Behavioural data.....142 - 148

8.1.3.1a Constant error.....143 - 144

8.1.3.1b Absolute error.....144 - 145

8.1.3.1c Individual differences.....146 - 148

8.1.3.2 Psychophysiological data.....148 - 167

8.1.4 Discussion.....168 - 171

8.2 **Experiment 4**.....172 - 190

8.2.1 Introduction.....172 - 174

8.2.2 Method.....174 - 175

8.2.3 Results.....175 - 188

8.2.3.1 Behavioural data.....175 - 180

8.2.3.1a Constant error.....175 - 176

8.2.3.1b Variable error.....178 - 179

8.2.3.1c Individual differences.....179 - 180

8.2.3.2 Psychophysiological data.....180 - 188

8.2.4 Discussion.....188 - 190

8.3 General discussion of experiments 3 & 4.....190 - 196

8.4 Conclusion.....196 - 197

Chapter 9: Experiment 5

Does mental practice improve performance ?

A further EEG study.....198 - 241

9.1 Introduction.....199 - 203

9.2 Method.....203- 209

9.3 Results.....209 - 234

9.3.1 Behavioural data.....209 - 217

9.3.1.1 Accuracy of recall.....210 - 213

9.3.1.2 Temporal data.....214 - 215

9.3.1.3 Individual differences.....216 - 217

9.3.2 Psychophysiological data.....218 - 234

9.4 Discussion.....234 - 241

9.5 Conclusion.....241

Chapter 10: Conclusion.....242 - 259

10.1 Imaginary transformation.....243 - 244

10.2 Movement Imagery.....244 - 250

10.3 Individual differences.....250 - 254

10.4 Summary.....254 - 256

10.5 Future Directions.....256 - 259

10.5.1 Imaginary Transformation.....256 - 257

10.5.2 Movement Imagery.....257 - 258

10.5.3 Individual Differences.....258 - 259

References.....260 - 284

Appendix A.....285 - 310

Appendix B.....311 - 318

Appendix c.....319 - 321

List of Tables

Table 5.1 Different EEG frequencies and their amplitudes.....79

Table 6.1 Summary of means and standard deviations of the VMIQ in the good and poor imagery groups (VMIQ).....95

Table 6.2 Electrodes at which main condition effects were observed in alpha.....98

Table 6.3 Electrodes at which main condition effects were observed in beta 1.....100

Table 6.4 Electrodes at which main condition effects were observed in beta 2.....102

Table 7.1 Electrodes at which main condition effects were observed in alpha.....120

Table 8.1 Details of the distance learned in the acquisition condition and the different interpolated activities use in each session.....142

Table 8.2 Summary of means and standard error of constant error.....144

Table 8.3 Summary of means and standard error of variable error.....145

Table 8.4 Summary of means and standard deviation of the VMIQ, MIQ and MRT.....146

Table 8.5 Electrodes at which main condition effects were observed in alpha.....151

Table 8.6a Electrodes demonstrating a change in alpha from the eyes open baseline to the acquisition (learning) condition.....152

Table 8.6b Electrodes demonstrating a change in alpha from the eyes open baseline to the recall condition.....152

Table 8.6c Electrodes demonstrating a change in alpha from the imagery condition to the acquisition (learning) condition.....152

Table 8.6d Electrodes demonstrating a change in alpha from the imagery condition to the recall condition.....152

Table 8.7 Summary of multiple regression analyses showing that MRT performance predicts changes in alpha from the eyes open baseline to the imagery condition.....153

Table 8.8 Electrodes at which main condition effects were observed in beta 1.....158

Table 8.9a Electrodes demonstrating a change in beta 1 from the eyes open

baseline to the acquisition (learning) condition.....159

Table 8.9b Electrodes demonstrating a change in beta 1 from the imagery condition to the acquisition (learning) condition.....159

Table 8.9c Electrodes demonstrating a change in beta 1 from the eyes open baseline to the recall condition.....159

Table 8.10 Summary of multiple regression analyses showing that MRT performance predicts changes in EEG from the eyes open baseline to the imagery condition in beta 1.....160

Table 8.11 Electrodes at which main condition effects were observed in beta 2.....163

Table 8.12a Electrodes demonstrating a change in beta 2 from the eyes open baseline to the acquisition (learning) condition.....164

Table 8.12b Electrodes demonstrating a change in beta 2 from the eyes open baseline to the recall condition.....164

Table 8.12c Electrodes demonstrating a change in beta 2 from the imagery condition to the acquisition (learning) condition.....164

Table 8.13 Summary of multiple regression analyses showing that MRT performance predicts changes in EEG from the eyes open baseline to the imagery condition in beta 2.....164

Table 8.14 Pearson correlations between frequency bands at prefrontal electrodes during acquisition and recall.....167

Table 8.15 Summary of means and standard error of constant error.....177

Table 8.16 Summary of means and standard error of variable error.....178

Table 8.17 Summary of means and standard deviation of the VMIQ, MIQ and MRT.....179

Table 8.18 Electrodes at which main condition effects were observed in beta 1.....183

Table 8.19a Electrodes demonstrating a change in beta 1 from the eyes closed baseline to the acquisition (learning) condition.....184

Table 8.19b Electrodes demonstrating a change in beta 1 from the eyes closed baseline to the recall condition.....184

Table 8.19c Electrodes demonstrating a change in beta 1 from the eyes closed baseline to the imagery condition.....184
Table 8.19d Electrodes demonstrating a change in beta 1 from the imagery condition to the acquisition (learning) condition.....184
Table 8.19e Electrodes demonstrating a change in beta 1 from the imagery condition to the recall condition.....184
Table 8.19f Electrodes demonstrating a change in beta 2 from the acquisition condition to the recall condition.....185
Table 8.20a Electrodes demonstrating a change in beta 2 from the eyes closed baseline to the acquisition (learning) condition.....187
Table 8.20b Electrodes demonstrating a change in beta 2 from the eyes closed baseline to the recall condition.....187
Table 8.20c Electrodes demonstrating a change in beta 2 from the eyes closed baseline to the imagery condition.....187
Table 9.1 A summary of the procedure in experiment 5.....205
Table 9.2 Mean accuracy and standard deviation of recall following physical and imaginary rehearsal.....211
Table 9.3 Duration of the physical and imaginary rehearsal of the sequence.....214
Table 9.4 Summary of means and standard deviations of the VMIQ, MIQ and MRT.....216
Table 9.5 Electrodes at which condition effects were observed in alpha.....221
Table 9.6a Electrodes demonstrating a change in alpha from the eyes open baseline to the Control 1 condition.....221
Table 9.6b Electrodes demonstrating a change in alpha from the eyes open baseline to the Control 2 condition.....221
Table 9.6c Electrodes demonstrating a change in alpha from the eyes open baseline to the Encoding condition.....221
Table 9.6d Electrodes demonstrating a change in alpha from the eyes open baseline to the Imaginary Rehearsal condition.....222

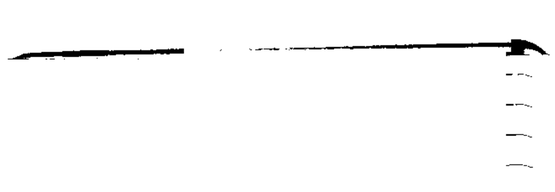


Table 9.7 Summary of multiple regression analyses in the alpha frequency.....224

Table 9.8 Electrodes at which condition effects were observed in beta 1.....228

Table 9.9a Electrodes demonstrating a change in beta 1 from the eyes open baseline to the Control 1 condition.....229

Table 9.9b Electrodes demonstrating a change in beta 1 from the eyes open baseline to the Control 2 condition.....229

Table 9.9c Electrodes demonstrating a change in beta 1 from the eyes open baseline to the Encoding condition.....229

Table 9.9d Electrodes demonstrating a change in beta 1 from the eyes open baseline to the Imaginary Rehearsal condition.....229

Table 9.10 Electrodes at which condition effects were observed in beta 2.....232

Table 9.11a Electrodes demonstrating a change in beta 2 from the eyes open baseline to the Control 2 condition.....233

Table 9.11b Electrodes demonstrating a change in beta 2 from the eyes open baseline to the Encoding condition.....233

Table 9.11c Electrodes demonstrating a change in beta 2 from the eyes open baseline to the Imaginary Rehearsal condition.....233

List of Figures

Figure 3.1 Overview of the hierarchical organisation of the motor system.....37

Figure 6.1 An item from the Vandenberg and Kuse Mental Rotation Test.....93

Figure 6.2 Alpha power during MRT and Eyes Open Baseline conditions.....96

Figure 6.3 Figure showing locations of main condition effects in alpha.....98

Figure 6.4 Beta 1 power during MRT and Eyes open Baseline conditions.....99

Figure 6.5 Figure showing locations of main condition effects in beta 1.....100

Figure 6.6 Beta 2 power during MRT and Eyes open Baseline conditions.....101

Figure 6.7 Figure showing locations of main condition effects in beta 2.....102

Figure 6.8 Mean alpha power of good and poor performance groups across MRT and eyes open baseline conditions.....104

Figure 6.9 Electrodes showing differences in alpha between good and poor (MRT) imagers.....105

Figure 6.10 Difference in alpha power between eyes open (EO) and mental rotation (MRT) in good and poor performance groups.....105

Figure 7.1 Mean alpha power at parieto-occipital sites in all three conditions.....118

Figure 7.2 Mean alpha power in good and poor (VMIQ) imagers 119

Figure 7.3 Electrodes showing differences in alpha between good and poor (VMIQ) imagers.....120

Figure 7.4 Electrodes showing differences in alpha between good and poor (MRT) imagers.....123

Figure 7.5 Electrodes showing differences in beta 2 between good and poor (MRT) imagers.....124

Figure 8.1 Mean constant error of recall of the criterion movements following the different types of interpolated activities.....144

Figure 8.2 Mean variable error of recall of the criterion movements following the different types of interpolated activities.....145

Figure 8.3 Pearson correlation showing relationship between Total scores of VMIQ and MIQ.....147
Figure 8.4 The relationship between the kinaesthetic component of the VMIQ and the visual component of the MIQ.....148
Figure 8.5 Power density recorded at P3 during all four conditions.....150
Figure 8.6 Figure showing location of main condition effect in alpha.....151
Figure 8.7 The relationship between MRT performance and the change in EEG from a baseline to the imagery condition.....154
Figure 8.8 Correlation of alpha power density at O1 with MRT performance.....155
Figure 8.9 Correlation of alpha power density at Oz with MRT performance.....155
Figure 8.10 Beta 1 power density during each condition recorded over left parieto-occipital cortex.....156
Figure 8.11 Figure showing location of main condition effects in beta 1.....158
Figure 8.12 The relationship between MRT performance and power density recorded at left parieto-occipital areas during the eyes open baseline.....161
Figure 8.13 Beta 2 power density during each condition recorded over right parietal cortex.....162
Figure 8.14 Figure showing location of main condition effects in beta 2.....163
Figure 8.15 Mean constant error of recall of the criterion movements following the different types of interpolated activities.....177
Figure 8.16 Mean variable error of recall of the criterion movements following the different types of interpolated activities.....178
Figure 8.17 Power density in beta 1 over anterior cortex (Fz) during each condition of experiment 4.....181
Figure 8.18 Power density in beta 1 over posterior cortex (Oz) during each condition of experiment 4.....182
Figure 8.19 Figure showing location of main condition effects in beta 1.....183
Figure 8.20 Power density in beta 1 over anterior cortex (Fz) during all four conditions of experiment 4.....186

Figure 8.21 Power density in beta 1 over posterior cortex (Oz) during all four conditions of experiment 4.....186
Figure 9.1 Illustration of 3*3 Matrix.....206
Figure 9.2 A comparison of the accuracy of recall following physical and imaginary rehearsal.....213
Figure 9.3 A comparison of the duration of physical and imaginary rehearsal.....215
Figure 9.4 The relationship between the visual and kinaesthetic components of the MIQ.....217
Figure 9.5 Alpha power density recorded at Pz during all five conditions.....220
Figure 9.6 Figure showing locations of condition effects in alpha.....221
Figure 9.7 The relationship between MRT performance and imagery related changes in alpha.....225
Figure 9.8 Correlation of alpha power density at P4O2 with MRT performance.....226
Figure 9.9 Beta 1 power density recorded at Pz during all five conditions.....227
Figure 9.10 Figure showing locations of condition effects in beta 1.....228
Figure 9.11 Correlation of beta 1 power density at P4O2 with MRT performance.....230
Figure 9.12 Beta 2 power density recorded during all five conditions.....231
Figure 9.13 Figure showing location of main condition effects in beta 2.....232
Figure C6.1 Experimental set up of experiment 1.....319
Figure C8.1 Experimental set up of experiment 3.....320
Figure C9.1 Experimental set up of experiment 5.....321

List of Abbreviations

ACQ	Acquisition
AE	Absolute Error
BEAM	Brain Electrical Activity Mapping
BP	Bereitshaftpotential
CE	Constant Error
CON	Counting Backwards
CON 1	Control 1 (encoding)
CON 2	Control 2 (imaginary rehearsal)
CON 3	Control 3 (recall)
CRT	Cathode Ray Tube
CT	Computerised Tomography
DLPFC	Dorsolateral Pre-Frontal Cortex
DRA	Defence Research Agency
EC	Eyes Closed
EEG	Electroencephalography
EMG	Electromyography
EN	Encoding
EO	Eyes Open
EOG	Electro-oculogram
ERP	Event Related Potential
FDG	Fluoro-deoxy- D-Glucose
FFT	Fast Fourier Transform
FMRI	Functional Magnetic Resonance Imaging
IDQ	Individual Difference Questionnaire
IPI	Imaginal Processes Inventory
IR	Imaginary Rehearsal
IUQ	Imagery Use Questionnaire

MEG	Magnetoencephalography
MI	Mental Imagery
MIQ	Movement Imagery Questionnaire
MIQ_K	Movement Imagery Questionnaire (Kinaesthetic)
MIQ_T	Movement Imagery Questionnaire (Total)
MIQ_V	Movement Imagery Questionnaire (Visual)
MP	Mental Practice
MR	Mental Rehearsal
MRI	Magnetic Resonance Imaging
NAM	Novel Actual Movements
NIM	Novel Imaginary Movements
PD	Parkinson's Disease
PET	Positron Emission Tomography
PMC	Primary Motor Cortex
PP	Physical Practice
PR	Physical Rehearsal
PSIS	Psychological Skills Inventory for Sports (PSIS)
QMI	Questionnaire upon Mental Imagery
rCBF	Regional Cerebral Blood Flow
REC	Recall
SE	Standard Error
SMA	Supplementary Motor Area
SPECT	Single Photon Emission Computed Tomography
STMM	Short Term Motor Memory
TVIC	Test of Visual Imagery Control
VB	Visual Buffer
VE	Variable Error
VMIQ	Vividness of Movement Imagery Questionnaire

VMIQ_K	Vividness of Movement Imagery Questionnaire (Kinaesthetic)
VMIQ_T	Vividness of Movement Imagery Questionnaire (Total)
VMIQ_V	Vividness of Movement Imagery Questionnaire (Visual)
VSSP	Visuo-Spatial Sketch Pad
VVIQ	Vividness of Visual Imagery Questionnaire
WM	Working Memory
X	Mean

Acknowledgements

I am deeply indebted to my Supervisors, Professor John Annett and Dr Gina Rippon for their advice, support and above all their patience. Although very sobering at times, their criticism has always been welcome and valuable. I also want to thank Barbara Stone and everyone at the DRA Farnborough, who assisted me in getting the experiments up and running. A special mention must go to Ken Puxley, Stuart King, Duncan Curwell and Mike Llewellyn for their assistance in repairing the equipment prior to the final experiment.

At Warwick, the enthusiasm and sheer hard work of Greg Milligan will never be forgotten. It is doubtful whether so much could have been achieved without his endeavours. Cheers Greg! Thanks must also go to Glyn for his advice and input into the statistical analysis. Thanks must also go to the departmental staff who never grumbled...at least not when I was listening!

The list could go on and on but I just want to thank Arlene, Nicky, Neil, Sarah and John P for making my time at Warwick a very happy one.

I should also like to the thank the EPSRC for their financial support during the period of study at Warwick.

Declaration

The work contained within this thesis is the sole work of the author. The research described in experiments 1 and 2 were published in Williams, J. D., Rippon, G., Stone, B. and Annett, J. (1995) Psychophysiological Correlates of Dynamic Imagery. *British Journal of Psychology*, **86**, 283-300.

Summary

Dynamic imagery refers both to the imaginary transformation of objects and to the imagination of bodily movements. It is hypothesised that dynamic imagery involves both motoric and visuo-spatial representations and to demonstrate that they operate at the cortical level of the brain, subjects' electroencephalograms (EEG) were recorded whilst they performed a variety of dynamic imagery tasks. It was further hypothesised that cortical activity recorded during these tasks would vary as a function of individual differences in imagery ability. Due to the lack of consensus on the validity both of 'objective' and 'subjective' measures of imagery ability, both kinds of instrument were used in this thesis. It was hoped that the EEG would provide objective evidence of the validity of these measures.

During imaginary transformation there was an increase in cortical activation over pre-frontal and parieto-occipital cortex, suggesting that high-level motoric and visuo-spatial representations are active during this task. No difference was observed in the EEG of subjects classified according to subjective report but differences were observed when they were classified according to task performance.

During movement imagery, an increase in activation over the pre-frontal and parieto-occipital cortex was observed, supporting the involvement of motoric and visuo-spatial representations. However, significant results were only obtained when the experimental task imposed sufficiently high cognitive demands on subjects. Only objective measures of imagery ability were correlated to imagery related changes in cortical activity. These studies demonstrate the difficulty of modifying behavioural tasks to suit the restrictions of the psychophysiological environment.

It is suggested that while having some benefit, the EEG presents major difficulties to the investigation of dynamic imagery. Given the restrictions of the experimental environment only simple movements are possible, thereby limiting the scope of experimental design.

Chapter 1

Introduction

Three main questions were addressed in this thesis:

1. Does dynamic imagery involve both motor and visuo-spatial representations?

2. Does the electroencephalogram (EEG) provide objective evidence of these representations at the cortical level of the brain?

3. Are subjective and objective measures of imagery ability related to one another, and do they predict imagery related changes in cortical activity?

Since the re-emergence of the mentalist approach to psychology, mental imagery has been at the forefront of research and has been the focus of considerable debate relating to the nature of cognitive representations. Most of this work has investigated visual imagery and has been somewhat restricted to an examination of the characteristics and properties of 'static' as opposed to 'dynamic' images. More recently, however, greater emphasis has been placed on dynamic imagery, a term which refers both to the imaginary transformation of objects in space and to the imagination of bodily movements.

1.1 Imaginary Transformations

Research has shown that processes involved in imaginary transformations operate in a manner that is analogous to processes encoding perceptual changes occurring when a physical object is rotated. Furthermore, evidence has been presented suggesting that the parietal cortex is crucial for this form of behaviour, e.g. patients with damage to the parietal lobe have impaired performance on such tasks compared to matched controls. Given the role of the parietal cortex in the integration of high level visuo-spatial information (Kosslyn, 1994) this evidence has been interpreted as demonstrating that the processes operating in imaginary transformations are visuo-spatial in nature.

More recently a number of researchers have also suggested that imaginary transformations involve motoric, in addition to visuo-spatial processes (Annett, 1990; Kosslyn, 1994; Paivio, 1986). For example, Paivio (1986) suggests that representations stored during the active manipulation of objects become active during imaginary transformation, while Kosslyn (1994) suggests that the motor system computes a feedforward model and is able to estimate the 'appearance' of an object subsequent to its transformation.

If imaginary transformation does engage motor processes it is likely that they operate at a relatively high level of the motor system (i.e. pre-frontal and pre-motor cortex) and are

involved in the planning and programming of movement. Any investigation of cortical activity related to imaginary transformation should, therefore, focus on these high level motor areas in addition to those cortical areas known to be involved in the processing of high level vision, i.e. the parietal cortex.

1.2 Movement Imagery

The imagination of bodily movement or Mental Practice (MP), is used extensively by high level athletes as part of their preparation for performance. Although not as beneficial as physical practice, it has been found to produce an improvement in performance when compared to no practice at all. Moreover, in combination with physical practice it produces a level of performance that is higher than that achieved after physical practice alone. However, although this phenomenon is widely accepted, the underlying mechanisms of MP are poorly understood.

A number of theories that have attempted to explain the effect of MP on performance, the most influential being the Symbolic-Perceptual Hypothesis (Sackett, 1934). This proposes that the observed improvement in performance is a result of the internal manipulation of cognitive representations which leads to the formation of movement related schemata. While there is strong evidence to support this top-down theory of mental practice, little detailed research has been conducted into the nature of the underlying cognitive representations. In this thesis, this question is addressed by examining cortical representations that become active when an individual engages in movement imagery taken from different perspectives.

A distinction is made in the literature between the 'internal perspective' (an individual imagines himself performing an action) and the 'external perspective' (an individual imagines someone else performing an action). These different forms of imagery are thought to involve motor/kinaesthetic and visual representations respectively (Mahoney

and Avener, 1987). It is argued that this description is too simplistic it being likely that imagery from either perspective involves *both* motor/kinaesthetic and visuo-spatial representations. Nonetheless, the distinction between these modalities is important given the large corpus of data concerning the nature of the information stored in these different representations. Any psychophysiological investigation of movement imagery should, therefore, be in relation to what is known about these different representations as it provides a clear framework within which specific hypotheses can be generated.

With regard to motoric information, Jeannerod (1994) suggests that imagery taken from an internal perspective involves much of the same information used in the preparation for actions, including their temporal organisation and parameters related to force. He skilfully draws on neuroscientific evidence to suggest that motor neural structures involved in the planning and pre-programming of movement e.g., the dorsolateral pre-frontal cortex and pre-motor areas, are also active during the imagination of movement. The clear implication of this hypothesis is that any examination of changes in cortical activity that occur during movement imagery should focus on these areas of cortex.

Of course one can not just refer to motoric representations when discussing dynamic imagery; voluntary movement involves the interaction of sensory and motor systems, so it is likely that sensory information, in addition to the motoric information described above, is stored in a representational format. The relative importance of these different kinds of information is considered to be dependent upon the perspective taken during imagery; although internal imagery is considered to be primarily motor/kinaesthetic there are certain circumstances when visual representations are also active. The same is true of external imagery; this form of activity has been likened to watching an 'internal video', and thus engages primarily visual representations. Evidence suggests however that parts of the motor system are active during the visual encoding of movement, so external imagery may also have a motoric element.

Although the hypothetical 'weightings' of these representations may depend on a given task, the fact that visual information is thought to be involved is important in the light of evidence from cognitive psychology. Evidence suggests that visual images maintain the structural characteristics of and produces effects on behaviour that are functionally equivalent to their perceptual counterparts. Moreover, cognitive neuroscience has produced powerful evidence demonstrating that cortical areas known to be involved in the processing of visual perception also become active during visual imagery. Thus, not only do visual images function as if they were percepts, but they also share common neural resources. Any examination of dynamic imagery related changes in cortical activity should, therefore, examine visual processing areas of the cortex.

1.3 The psychophysiological approach

Changes in neural activity associated with dynamic imagery have been examined using both regional cerebral blood flow (rCBF) methods and the EEG, though both methods have produced conflicting results concerning cortical areas that become active during imagery. For example, Roland, Larsen, Lassen and Skinhoj (1980) reported that the primary motor cortex is inactive during movement imagery, whereas Breitling, Guenther and Rondot (1986) reported that is active. Although the rCBF has relatively precise spatial resolution, it has poor temporal resolution. In contrast the EEG has poor spatial resolution but good temporal resolution, so it was decided to investigate patterns of cortical activity associated with dynamic imagery using this method.

The important question is of course whether the use of the EEG is suitable for the proposed investigation. In any examination of the functional equivalence of movement and imagery, one of the control conditions should allow measurement of EEG during the actual movement to be imagined. As neural activity in the EEG is masked by electromyographic (EMG) activity this could provide a major methodological problem so any movements should have very few degrees of freedom to avoid the problem of muscle

related artifact in the EEG signal. At the same time it is important to keep in mind that the complexity of the motor system makes it likely that dynamic imagery involves widely distributed cortical processes, so this movement has to impose sufficient cognitive demands on the subject to produce observable changes in the EEG during imagination.

Psychophysiological methods have been used to demonstrate that the visual imagery and perception share common neural resources. Tasks used in these studies (e.g. Farah, Peronnet, Gonon & Giard, 1988) were typically adapted from cognitive paradigms used to demonstrate the functional equivalence of visual imagery and perception. It was hoped that a similar approach could be adopted in the experiments reported here, i.e. incorporate tasks or modify tasks that have been used to demonstrate the functional equivalence of movement and dynamic imagery.

The question of what constitutes a valid baseline in EEG is also a major theoretical problem in this kind of research. Most EEG studies typically use a 'resting' condition in which the EEG is recorded while subjects sit quietly either with their eyes open or their eyes closed. They are instructed to think about nothing, and although there is no way of ensuring that subjects abide by these instructions, it is generally accepted that there are less cognitive demands made on the subject during this condition compared to an experimental task. Thus, any difference in EEG activity is thought to reflect task related processes.

It is possible that the subtractive method would provide a more accurate and representative baseline. This approach is used widely in rCBF studies; the control task and the experimental task differ only with respect to a single set of processes so any difference in blood flow between the conditions is hypothesised to reflect these processes. One potential difficulty is that, compared to the rCBF techniques, the EEG has very poor spatial resolution; dynamic imagery involves a number of widely distributed cortical processes and the EEG may not have sufficient sensitivity to detect what are likely to be

very small changes in cortical activity. Nonetheless, this approach might provide more detailed information of task related changes in EEG, so as well as using the more traditional 'eyes open' and 'eyes closed' baselines one of the experiments reported here also used the subtractive method.

In conclusion, it is suggested that the EEG presents difficulties in an investigation of changes in cortical activity occurring during dynamic imagery. The development of a suitable experimental task and the choice of a valid baseline present major methodological problems. However, in comparison to blood flow techniques it has superior temporal resolution, is non-invasive and more adaptable for a wide range of tasks. For these reasons the EEG was the technique used in this thesis.

1.4 Individual Differences

Although the idea of fixed cognitive architectures is one of the central tenets of cognitive science, it is obvious that there are considerable individual differences in every form of cognitive activity. This is especially true of mental imagery. Any examination of dynamic imagery related changes in cortical activity should, therefore, attempt to account for these differences as they may have profound consequences on how information is represented in the brain and by implication will affect the strength of activity recorded over cortical areas thought to be engaged during dynamic imagery.

Unfortunately, individual differences in imagery ability is one of the weakest areas of imagery research and no clear explanations have been provided as to how this important variable affects imagery related performance. The main problem is how best to assess imagery ability. The most common instruments are questionnaires that provide a self-rating score of the vividness of an evoked image and performance tests that are deemed to require the use of imagery processes in order to solve a particular problem. The first instrument is fraught with difficulties, its main weakness being that it provides only a

subjective assessment of an ill-defined qualitative aspect of an image. The second instrument is favoured by many as it produces an objective measure of imagery ability. Although this approach provides an observable response, the interpretation of these data is based solely on the theoretical assumption that imagery is involved in these tasks. Therefore, although both types of instrument provide useful information, each method has its own particular weaknesses.

It was decided to assess the relative merits of objective and subjective measures of imagery ability by incorporating them into this investigation of cortical activity associated with dynamic imagery. An examination of the relationship between the EEG and these instruments of imagery ability might provide important information as to the validity of these measures.

1.5 Summary

The main hypothesis of this thesis is that dynamic imagery involves both motoric and visuo-spatial representations, though the relative strength of each type of representation may depend both upon the type of dynamic imagery that is evoked (movement imagery or imaginary transformation of objects), and the perspective adopted by the individual (internal vs external perspective) during imagery. Given evidence from cognitive psychology and cognitive neuroscience suggesting that motoric and visuo-spatial imagery involves specific areas of the cortex, the EEG may provide important evidence for the existence of these processes.

It is further hypothesised that subjects of varying imagery ability will exhibit different patterns of cortical activity during the performance of an imagery related task. The EEG, in addition to providing an objective measure of imagery ability, might also allow an examination of the usefulness of 'objective' and 'subjective' instruments of imagery ability. It is hoped that by examining these measures, both in relation to each other and in

relation to subjects' cortical activity, a valid and consistent measure of imagery ability can be achieved.

In order to develop these arguments in more detail, this thesis is structured so that it first provides the reader with an understanding of the previous research literature and how it relates to the general hypotheses, and then describes a series of experiments which test more specific predictions related to these hypotheses. Chapter 2 gives an account both of the different types of dynamic imagery and of the hypothetical properties of the underlying representations. In an attempt to highlight those areas of the brain that are likely to be involved in dynamic imagery chapter 3 discusses evidence from cognitive neuroscientific data from normal and brain damaged populations. Chapter 4 outlines the traditional approaches used in the assessment of individual differences and discusses their weaknesses and their success at predicting individual differences in psychophysiological data. Chapter 5 describes the methodology and statistical analysis adopted in each of the experiments reported in this thesis. Chapters 6 to 9 provide detailed accounts of five experiments that examined the relationship of objective and subjective measures of imagery ability to imagery related changes in cortical activity. Finally, Chapter 10 offers a summary of the main findings of these experiments and a statement of whether they support the main hypotheses. It concludes with an assessment of the successes and failures of these endeavours and offers some suggestions for future research.

Chapter 2

Dynamic imagery - visual, spatial or motoric representations?

A common distinction in the literature is made between 'static' and 'dynamic' imagery (Kosslyn, 1994; Paivio, 1986; Paivio & Clark, 1991). Given the phenomenological nature of imagery and the ease of introspection, the distinction appears straightforward, yet an examination of the literature, particularly with reference to dynamic imagery, shows that there is considerable confusion and little agreement regarding the nature of the underlying representations. The term 'dynamic' is used to refer to:

1. The imaginary transformation of objects in space.

2. The imagination of movement, which can be further divided into:

a) imagery from an 'internal' perspective.

b) imagery from an 'external' perspective.

There are, therefore, three different forms of dynamic imagery. As this thesis is concerned with the measurement of cortical activity during dynamic imagery it is important to understand the nature of these representations. The purpose of this chapter is to review the literature concerning dynamic imagery with an aim to describe the representations underlying these 3 different forms of imagery.

2.1 Imaginary transformation

Most investigations of imaginary transformations have focused on the mental rotation paradigm. The major investigation into mental rotation was conducted by Shepard and Metzler (1971) who presented subjects with pairs of drawings of 3 dimensional figures, the task being to decide whether they were identical or different in shape. In some trials figures were identical but rotated either in the picture plane or in the depth plane, the angular disparity of the 'target' and 'test' items being varied systematically. In other trials the figures were different in shape. Results showed that when the figures were identical, subjects' decision time increased relative to the angular disparity between the target and test items. A number of different studies have replicated this study using alphanumeric characters (Shepard & Cooper, 1973), polygons (Cooper, 1975; Farrell & Shepard, 1981), faces (Cochran, Pick & Pick, 1983) and photographs of faces (Valentine & Bruce, 1988). Results of these studies suggests that the increase in mental load relative to the increase in the angle of rotation is similar to the increase in effort that is required to physically rotate an object. It also suggests that the limitations inherent to the physical process are a characteristic of their representational counterparts.

Evidence supporting this argument was reported by Cooper (1976). Following an assessment of speed of rotation, subjects were presented with a target figure and had to imagine rotating it in a clockwise direction. At certain times during this period, a test figure was presented in one of twelve different orientations and subjects were required to indicate whether it was identical to, or a mirror image, of the target figure. Results

showed that the decision times were shortest when the test figure was congruent with the assumed orientation of the mental representation of the figure that had been calculated on the basis of subjects' speed of rotation. There was also a linear relationship between decision times and the degree of incongruence between the assumed orientation of a mental representation of a figure and the orientation of the test figure. These data have been interpreted as showing internal representations of an object change as they go through a series of incremental transformations during rotation: more transformations are required the greater the angular disparity between a target and test item. The transformation process is thought to operate in a fashion that is analogous with those processes that allow a percept of an object to change as it is physically rotated.

The successful transformation of images is generally considered to involve a number of complex processes (Fischer & Pelligrino, 1988) and to date there is no definitive model that encapsulates the sheer variety of experimental data that have been reported in the literature. The most comprehensive and influential model is that of Kosslyn (1980;1994), the most recent version of which proposes that imaginary transformation involves both motoric and perceptual processes. Kosslyn (1994) sets out a very detailed model of imagery transformation invoking a large number of processing modules, each of which combine to produce behavioural effects that are analogous to those operating in high level vision. A detailed analysis of his model is, however, beyond the scope of this thesis and any discussion will be restricted to perceptuo-motor processing.

2.1.2 The role of motor processes in the imaginary transformation.

The idea that motor processes are involved in image transformation is not new; Paivio stated that "all mental transformations engage motor processes that derive originally from active manipulation of their referent objects" (Paivio, 1986, page 73) and similar ideas have been expressed by Annett (1990) and Weimer (1977). Some of the strongest evidence for the involvement of the motor system in image transformation have come

from studies that have involved the mental rotation of body parts. Cooper and Shepard (1975) presented subjects with rotated pairs of hands, either palm up or palm down, the task being to decide whether the hands were both right or both left. As in other studies of mental rotation, response times increased with the degree of angular disparity, but more importantly subjects appeared to mimic the movements of their hands to solve particularly difficult items in the test. Parsons (1987a, b) demonstrated that the time taken to mentally rotate one's hands and feet took much longer when the actual physical rotation would have been difficult, suggesting that internally simulating the rotation of the hands and feet is analogous to physical rotation. Similar results were reported by Sekiyama (1983) who found that it took longer for subjects to mentally rotate their hands in an anti-clockwise direction.

Evidence from animal studies has also implicated motoric processing in such transformations (Georgopoulos, Lurito, Petrides, Schwartz & Massey, 1989). In this study, monkeys were trained to move a handle to a light that was presented in the middle of a screen. The light was then switched off and after a short delay, a second light (dim or bright) appeared in one of eight different positions. When the bright light appeared the monkey had to move the handle counter clockwise to a position perpendicular to the light; when the dim light appeared, it had to move the handle to the light. Single cell recording of cells in the primary motor cortex showed that different cells fired according to the different position of the monkey's arm. That is, cells fired before the movement onset and individual firing patterns were related to the expected position of the arm subsequent to movement. Moreover, the temporal pattern of the firing of these neurons showed that cells fired in series depending on their position in the expected trajectory, suggesting that they internally rotated the position of its limb. Although this study does not highlight the exact locus of the transformation process, it does show that the motor system is active during the internal computation of a purposive movement.

Other evidence implicating the motor system in mental rotation has been provided by those studies that have shown congenitally blind subjects produce similar behavioural characteristics as sighted individuals (Marmor and Zabeck, 1976). These results imply that internal representations of objects in blind people are encoded via haptic, rather than visual experience and that mental rotation is based on kinaesthetic and motor representations.

2.1.2 The role of visuo-spatial processes in the imaginary transformation.

In sighted subjects it is evident that imaginary transformation involves visuo-spatial mechanisms. Corballis and McLaren (1982) found that the observation of a rotating disc prior to a mental rotation task caused motion after-effects and resulted in subjects rotating the stimuli in the opposite direction to the disc. Jolicoeur and Cavanagh (1992) presented subjects with letters at various orientations, either in a normal or a mirror image perspective. Then either the letter or the background was rotated. Results showed that interference occurred if the letter physically rotated but not if the background rotated. Both studies demonstrate the involvement of visuo-spatial processing in mental rotation.

The question arises as to the relative strengths of the different visuo-spatial and motor representations and how they interact during image transformation? Quinn and Ralston (1986) and Logie and Marchetti (1991) proposed that movements selectively interfered with working memory, while others have shown that the imagination of movement sequences disrupts working memory (Quinn, 1991; Smith & Pendelton, 1989). This evidence suggests that under certain circumstances the motor system 'drives' the transformation of images. Kosslyn (1994) distinguishes between "motion encoded" and "motion added" transformations: the former type of imagery refers to representations stored during the observation of an object in motion, the latter to the active manipulation of an object, as for example during mental rotation. He proposes that "motion added" transformations are driven by the motor system and are instrumental in predicting the

outcome of a given manipulation. Although he doesn't describe it as such, Kosslyn is describing a forward model in motor processing, an idea that is not new: a similar role in the control of complex movements has been suggested by Mel (1988). Brown, Britain, Elvevag and Mitchell (1994) suggest that the caudate loop of the cortico-striatal system is crucial in the computation of such models and have argued that damage to this system underlies specific deficits in Parkinson's Disease and schizophrenia. Indeed, Grush (1994) suggests that the effects of mental practice may be explained by reference to a forward model. It computes the expected outcome of a purposeful action on the world (given the present state of the organism and it's environment) which acts as a template for comparison when the action is performed.

While evidence suggests that the motor system is important in image transformation, it is argued that there is insufficient evidence to support Kosslyn's proposal that motoric representations 'guide' the transformation by anticipating particular changes in the relevant representations. Movement is dependent on the close interaction of the visual and motor systems; the motor system may anticipate what will happen but this mechanism is dependent on information about the current state of the organism in the environment which it receives primarily, though not exclusively, from vision.

2.2 Movement Imagery

Imagery of movement has been used extensively in a variety of applied settings, though it is best known in the context of athletic performance when it is used as a means of acquiring or improving motor skills. A number of different terms have been used to describe this form of mental activity including visualisation, mental rehearsal and mental practice. In this thesis the description Mental Practice (MP) is used synonymously with imagery of movement. At the outset, a distinction must be made between the more general term 'mental preparation' and the more specific term MP. The former term refers to a variety of procedures ranging from preparatory arousal or "psyching-up", to

attentional focus, self-efficacy statements, relaxation procedures and mental imagery. The latter term is used to denote "the symbolic rehearsal of physical activity in the absence of any gross muscular movements" (Richardson, 1967a). By this is meant that a subject imagines enacting a particular skill or part of a skill that is, in most cases, about to be performed.

MP is by no means a recent phenomenon and can be traced as far back as the 1890s. James (1890) refers to it in his *Principles of Psychology* and Wiggens (1984) refers to William Anderson, a physical instructor who in 1897-1898 performed a number of experiments on the effects of imagery. The basic paradigm employed in MP experiments incorporates a three condition design, with independent groups of subjects being randomly assigned to each of these conditions. All three groups engage in a pre-test of a task to provide an initial measure of performance. One group is then provided with physical practice (PP) of that task, another group mentally practises (MP) the same task for the same number of trials and a third group acts as a control and perform a different task. A fourth condition is sometimes included and involves a combination of PP and MP. All groups then receive a post-test assessment on the task under conditions that are identical to those in the pre-test. If performance improves in MP and PP groups but doesn't improve in the control group, then it is assumed that the activity interpolated between pre and post-test assessment is responsible for this improvement.

The efficacy of MP on subsequent performance has been supported by some research (Ryan & Simons, 1982), but has not been confirmed by others (Cronk, 1967; Smith & Harrison, 1962). The most common finding is that PP results in better performance than MP, which in turn improves performance compared no practice (Egstrom, 1964; McBride & Rothstein, 1979; Mendoza & Wichman, 1978). Other studies have demonstrated no difference between MP and PP though both produce better performance than no practice (Kohl & Roenker, 1980; Rawlings, Rawlings, Chen & Yilk, 1972; White, Ashton, Ashton & Lewis, 1979; Wrisberg & Ragdale, 1979). A combination of PP and MP has been

found to produce an improvement in performance which is equal to PP (Egstrom, 1964; Stebbins, 1968) and even greater than PP (McBride & Rothstein, 1979; White *et al.*, 1979).

An early review of 25 studies concluded that most studies provide evidence of the efficacy of MP, though the overall evidence was weak (Richardson, 1967a; 1967b). In a meta-analysis of 60 studies, Feltz and Landers (1983; updated in Feltz, Landers & Becker, 1988) reported that MP resulted in a moderate improvement in performance compared to no practice but was considerably less effective than PP. They also concluded that the effects of MP were much greater for cognitive tasks compared to motor or strength tasks. Driskell, Copper and Moran (1994) argue, however, that any overall improvement in performance reported by Feltz and Landers can not be explained by MP alone but could be a result of any combination of 'mental preparation' techniques. Driskell *et al.* performed a meta-analysis of data collected according to considerably more restrictive criteria than previous reviews, i.e. studies were excluded if they used any form of intervention other than MP. Their analysis indicated that MP has a significant though moderate effect on performance although this was significantly less effective than PP. More detailed analysis showed that MP is an effective intervention for both cognitive and physical tasks, the optimum effect being when MP is followed immediately by performance. Furthermore, improvement of novices' performance was greater for cognitive tasks compared to physical tasks, though no difference in experts' performance was found between cognitive and physical tasks.

Opinions vary as to the those individual likely to benefit from MP, what type of task most readily lends itself to MP and the conditions under which it is likely to have the greatest effect. Some researchers (e.g. Sackett, 1934; Ryan & Simons, 1981) suggest that MP is more beneficial for cognitive tasks and has little or no effect on the performance of physical tasks. In line with this suggestion, Schmidt (1982) proposed that MP improves performance during the initial stages of learning and is, therefore, of more use to novices

than experts. This makes sense given Fitts and Posner's (1967) 3 stage model of learning; MP employed prior to physical activity would provide schematic knowledge of the task and would provide important procedural knowledge during initial stages of learning. There is no consensus on this point and Zecker (1982) has argued that a lack of physical practice may actually hinder novices as they may develop representations that are inappropriate for the task.

In conclusion, it is widely accepted that MP does have a beneficial effect on performance of both cognitive and physical tasks, though it lends itself more readily to perceptuo-motor tasks with a large cognitive component. It must be said, however, that most of these studies offer little or no explanation of the cognitive or physical mechanisms involved in MP. There are a number of theories as to how MP has an effect on performance including the motivational hypothesis (Paivio, 1986), the psychoneuromuscular theory (Richardson, 1967b) and the symbolic rehearsal account (Sackett, 1934), but as Annett (1995) points out, no single theory can explain all the data reported in the MP literature. It is likely that different elements of these theories combine in a manner that is specific to the task and to the skill and motivation level of the subjects used in a particular study. As this thesis adopts a centralist view of the effects of imagery, the symbolic perceptual hypothesis is of most interest and so only this theory will be discussed in any detail.

2.2.1 The symbolic-perceptual theory of movement imagery

First suggested by Sackett (1934), this hypothesis proposes that the effects of MP can be explained in terms of the cognitive processing and manipulation of stored representations. It is based, in part, on the assumption that MP is more effective in the early stages of learning and improves the cognitive component of a task more than the motor component (Ryan & Simons, 1981, 1983; Wrisberg & Ragdale, 1979). The strongest evidence to support this theory has come from studies that have used the bilateral transfer paradigm

that is based on the principle that learning exhibits partial transfer from one task to another. In this context it refers to the ability of being able to learn a particular skill more easily with one limb after the skill has been learned by the opposite limb. Cognitive elements of the task are learned irrespective of the limb engaged in active practice, so that the non practised hand does not have to learn these elements and so starts at a higher level of proficiency than if no practice had occurred (Ammons, 1958).

A series of experiments reported by Kohl and Roenker (1980) provided strong evidence supporting the symbolic perceptual theory of MP. Subjects were divided into three groups; PP, MP and control. The PP group practised a pursuit rotor task with their right hand. The MP group observed the experimenter perform a single trial on the task and then imagined themselves performing the task. The control group had no PP or MP. Results showed that there was no difference between the PP and MP groups on the transfer trials though both groups performed significantly better than the control group. These experiments provide strong evidence of the cognitive components of MP.

Further evidence of cognitive mechanisms in MP was produced by Johnson (1982) who demonstrated that MP produced equivalent biasing effects to PP on recall of a previously learned movement. Johnson also showed that the effect of MP did not occur when subjects were subjected to visual interference during MP, whereas the biasing effects were increased when subjects were subjected to motor interference. This suggests that imaginary rehearsal of this task has a cognitive rather than a motor component. More recently, Hall, Bernoties and Schmidt (1995) reported similar effects of MP adding support for the symbolic perceptual hypothesis.

Psychophysiological data has also been interpreted as supporting top down mechanisms in MP, particularly those that show a close relationship between changes in autonomic activity and motor commands. Correlations between autonomic measures and physical action have been observed when subjects imagine performing the action (Beyer, Weiss,

Hansen, Wolf & Seidel, 1990). Decety, Jeannerod, Germain and Pastene (1991) recorded cardiac and respiratory activity of subjects when they were imagining running on a treadmill at different speeds. They reported a positive correlation between the degree of mental effort and changes in these different measures, i.e. respiratory and cardiac rate increased as the rate of the imagined running increased. More importantly they also found that oxygen uptake actually decreased during MP demonstrating that the increase in autonomic activity is greater than the necessary metabolic requirements (cf. Decety, Jeannerod, Durozaed and Baverel (1993).

These psychophysiological data are important as they suggest that at least part of the autonomic activity is centrally controlled in a manner analogous to that operating in anticipation of movement. Changes in heart rate and breathing occur within 5 beats of exercise beginning (Adam, Guz, Innes & Murphy, 1987; Krough & Lindhard, 1913), an effect which is too rapid to be caused by metabolic factors as in increase in CO^2 in the venous blood takes considerably longer. This implies that an action plan is represented at a cognitive level of the motor system and may be observed as cortical activity during preparation. The bereitschaftspotential (BP), an evoked potential which has a maximum amplitude over the vertex and occurs up to 800 ms before onset of movement is an example of such activity. It has been interpreted as reflecting the activation of the Supplementary Motor Area (SMA) which operates at a relatively high level in the hierarchical control of movement and is principally involved in the preparation and timing of a complex series of movements (Deeke & Kornhuber, 1978; Deeke, Kornhuber, Lang, Lang & Schreiber, 1985).

Evidence pertaining to the BP is important if one considers that mental practice has its effect on performance because movement images may activate the same processes used in the preparation for overt action. Jeannerod (1994) suggests that a motor image can be equated with preparation for action; the representations of the action plan become available for conscious inspection in the form of an image when the plan is not translated

into action. During mental practice these representations are consciously manipulated in such a way that it has a direct effect on performance. If this view of mental practice is accepted then one should examine activity in those cortical areas known to operate at the highest level of the motor system. The pre-motor and pre-frontal cortex have both been implicated in the planning and organisation of movement, so these areas should become active during movement imagery, reflecting cognitive top-down mechanisms that affect lower levels of the motor output system.

Research suggests then that mental practice has a large cognitive component and may involve neural motor structures that are involved in the planning and preparation for action. However, purposive action involves the complex interaction of motoric processes and perceptual information from the external environment. Indeed it is more accurate to discuss perceptuo-motor activity rather than motor activity *per se*. Any theoretical account of MP must consider the nature of perceptual information encoded during action. In the introduction to this chapter a distinction was made between the internal and external perspective taken during imagination, as they likely involve distinct and separate sensory representations. This implies that different areas of cortex may be active during internal and external imagery as sensory information is processed by different areas of the cortex.

2.2.2 Movement imagery - the 'internal' and 'external' view.

An internal perspective is taken when a subject imagines himself performing a particular action, whereas an external perspective is adopted when he imagines someone else performing an action. During internal imagery the subject experiences the effort and sensation of producing an action by consciously activating representations involved in the generation of forces necessary for the successful completion of a given action (Jeannerod, 1994). During external imagery subjects attend to a 'mental video', produced by the activation of those representations encoded and stored during observational learning. The

adoption of an internal or external perspective is said to engage motor/kinaesthetic and visual imagery respectively (Mahoney and Avener, 1987). This is an obvious over-simplification resulting from an inadequate definition of what constitutes internal and external imagery.

In the case of external imagery, as when a learner watches a model perform a particular sequence of movements, it is assumed that a visual representation of the action is encoded into a symbolic code which can then be internally rehearsed as in the mental video scenario. For example, Annett (1990) and Whiting and den Brinker (1981) have proposed that during observation, learners extract a dynamic high order visual gestalt (an image of the act) which when rehearsed consolidates the temporal and spatial characteristics of the sequence. More recent evidence suggests that observational learning also has a motor component. In an experiment using the single cell recording technique, di Pellegrino, Fadiga, Fogassi, Gallese and Rizzolati (1992) discovered that cells in the rostral inferior pre-motor cortex of *macaca nemestrina* fired not only prior to and during a particular action, but also when the monkey observed the experimenter performing the same action. This implies that the adoption of an external perspective during imagery may involve visual *and* motor kinaesthetic representations, though the mechanism that transforms visual input into motor output is a question of debate and depends very much on the theoretical stance of the investigator.

In the case of internal imagery, as when an high jumper imagines himself running up to and clearing the bar, it is assumed that the imagery is motor/kinaesthetic in nature (Taylor, 1993). However, it is unlikely that the subject evokes only this kind representations as the relevant body sensations are probably encoded in reference to what the athlete sees as he approaches and jumps over the bar. Pure motor/kinaesthetic imagery in this scenario will not have any 'meaning' and so internal imagery of this kind probably comprises visual and motoric information. It is possible, however, that the motoric

representations has a greater 'weight' in the composition and effectiveness of this type of imagery compared to visual representations.

Consider next a scenario where the environment is less fixed, as in a ski slalom; the perceptual information encoded by the skier is constantly changing and so an 'internal visual' perspective is recommended during imagery as the relevant information would be unavailable during observational learning (cf. White & Hardy, 1995). The adoption of this perspective does not imply that the image is purely visual; visual information acts as a cue for appropriate motor output, so the relevant motor information may also be activated during imagery (even if the intention is to generate an internal visual image!). This type of internal imagery may also be a composite of both visual and motor representations, but in this case the visual information may have a greater 'weight' in the image. The same may be said for skills that involve complicated eye hand co-ordination such as tying a bow (cf. Annett, 1986).

Although the relative importance of visual and motor representations in a given image is hypothetical and may be dependent upon the task being rehearsed, there is no doubt that mental practice taken from either perspective involves different combinations of motor/kinaesthetic and visual information. Any interpretation of imagery related cortical activity should, therefore, be approached in relation to what is known about these different kinds of representation.

2.2.2.1 Movement Imagery - properties of motor representations

Jeannerod (1994) conceptualised movement imagery as being equivalent to those representations involved in the intention and preparation for action. The only difference between the two forms of processing is in their subjective nature: the contents of a goal plan do not reach consciousness when the appropriate actions are executed, only the end

result being available for conscious assessment. When the goal plan is not translated into action the contents of these representations reach consciousness in the form of imagery.

A similar model of motor imagery has been proposed by Annett (1982; 1986; 1990; 1995). Annett distinguishes between unconscious information that is stored in long term memory and conscious information that is manipulated in a working memory medium (cf. The visuo-spatial sketchpad: Baddeley, 1986). Information of the form of simple movements (action prototypes) are stored in long term memory. When overt action is inhibited, i.e. during MP, perceptual information is retrieved from long term memory and manipulated according to the specific spatial and temporal parameters necessary for the successful completion of the intended action. This allows a comparison of imagined action with the intended motor output.

Jeannerod's theory implies that if it were possible to distinguish representational properties of an 'action plan', then the structure and contents of images of movement could be described. If it were found that information such as the force and duration of a particular movement are stored in an action plan then his theory becomes compatible with Annett's model and together these theories may provide an explanation (albeit elementary) of how motor and visual representations might interact during MP.

A number of studies have examined the question of how the temporal structures of movement are organised, the general consensus being that there is a close similarity in the time taken to mentally rehearse and physically produce a movement. Landauer (1962) reported almost identical times for overt and implicit recitation of the alphabet. Decety and Michel (1989) reported no difference in the time taken to actually write or imagine writing a signature, irrespective of which hand was used. In a study which investigated imagery of whole body movement, Decety, Jeannerod and Prablanc (1989) found no difference between the walking times to targets of variable distance and the time taken to imagine walking to these same targets.

If temporal characteristics of movements are encoded in action plans then force may also be represented, as duration of action depends on the relationship between mass and force. Decety *et al.* (1989) reasoned that if force is represented centrally then the duration of actual and imagined movements performed against an external load should differ as the load would only exert its effect in the overt condition. In an experiment similar to that described above, subjects wore a rucksack containing a 25 Kg weight and were instructed either to walk to or imagine walking to a target. The duration of the imaginary walks was significantly longer during the overt condition suggesting that the representation of force rather than duration is the crucial mediating variable. Further evidence suggesting that force is represented centrally has been provided by those studies that have examined the subjective sensation of effort in partially paralysed subjects (Gandevia, 1982; Gandevia & McCloskey, 1977).

2.2.2.2 Movement Imagery - properties of visual representations

Kosslyn (1980;1994) has attempted to systematically describe the internal structure of visual images and how different processes act on them. He has proposed that the representations underlying mental imagery are analogical, that is to say, they have an internal structure and a set of processes acting upon them that function in a manner that is analogous to those derived from direct perception. As such they maintain a structural "second-order isomorphism" (cf. Shepard, 1980) with those perceptual representations. At the core of his work is the metaphor of the cathode ray tube (CRT); images are generated from long term storage into a short term visual store called the "visual buffer" (VB) which has defined spatial characteristics and functions as if it represents a co-ordinate space. The VB is shared with perception so that the same 'pixels' are activated during the perception of an object and when an image of that object is generated from long term memory. He describes the representations of that image as being quasi-pictorial

in nature; what he means by this is not that they are identical to the actual object but that they maintain and represent its spatial characteristics viewed from a particular viewpoint.

Kosslyn has attempted to show that the characteristics of the VB are subject to the same limitations as the perceptual system. For example, he demonstrated that composite elements of an imaged object cannot be resolved if the object itself is too small, indicating that the VB has a specific grain (Kosslyn, 1975). The VB has also been shown to have limited spatial extent; when an object is imagined from a near perspective there reaches a point, as in perception, where the imagery system is unable to process all the information simultaneously and the image "overflows" resulting in parts of the image having to be excluded. From this, Kosslyn argues that the internal structure of the VB reflects the organisation of the retina; receptive fields of retinal cells are larger and less sensitive to detail in the visual field as the distance from the fovea increases. This should not be taken literally but interpreted as showing that the VB functions in a manner that is similar to the retina.

Kosslyn does not consider imagery to be a unitary concept but argues that it is comprised of different modules or components which manipulate the information in the VB. He describes 3 main processes which "generate", "inspect" and "transform" visual images: there are many more processes described in his theory but these are the most important and will suffice for the purpose of this discussion. The *generation* process retrieves visual and spatial information about an object from long term memory and creates an image in the VB. The *inspection* process allows a detailed examination of the spatial arrangements of its composite elements. The *transformation* processes allow, amongst other things, an image to be rotated or changed in scale. What is important about each of these processes is that they are consciously initiated by the individual during imagery .

The work of Kosslyn is important as it suggests that the spatial characteristics and properties of the visual world are retained in a representational format. The significance for MP is clear; if the information stored and manipulated in visual images is isomorphic with veridical seeing then it is possible, as in the case in observational learning, that attention directed to relevant information in an image may allow some form of translation from visual to motoric codes.

2.2.2.3 Movement Imagery - visual or visuo-spatial representations ?

In the previous sections reference has been made to the fact that MP comprises distinct motor/kinaesthetic and visual representations that interact according to the perspective taken by the subject. The question remains as to whether sensory representations used in imagery comprise purely visual or visuo-spatial information? Johnson (1982) argued, on the basis of his experimental evidence, that the effects of imagery on the retention of movement information in memory was caused by "high level" visuo-spatial processes. Indeed, similar studies have demonstrated that the end *location* of a movement is recalled more efficiently than the distance of the movement (e.g. Laabs, 1973). That is to say, spatial processes are crucial for the retention of this kind of movement information.

Before discussing the role of spatial information in MP it is necessary to define the term 'spatial'. In this thesis, it is used to describe those processes that are involved in the production of accurate movements to positions in space and in the computation of the geometrical relationship of two or more components of an object. Most of the research that alludes to a distinction between visual and spatial representations has been in relation to Working Memory (WM) (Baddeley, 1986; Baddeley and Hitch, 1974; Baddeley and Leiberman, 1980; Logie, 1995). The basic WM model comprises two sub-systems that process verbal and visuo-spatial information respectively. Both components consist of a temporary working store where information, either retrieved from long term memory or accessed via sensory data from the environment, is manipulated by a series of executive

processes. In the case of visuo-spatial processing, it was proposed that information is temporarily stored and manipulated in a sensory buffer called the visual-spatial sketch pad (VSSP) (Baddeley, 1986). The VSSP is very similar to Kosslyn's 'visual buffer' and the processes that he describes in his model (image generation, transformation etc) can be equated with the executive functions put forward in the WM model.

Most of the studies investigating the characteristics of the VSSP have used variations of the Brooks Matrix Task (Brook, 1967) which is assumed to involve imagery. In this task, subjects were instructed to visualise a 4 by 4 matrix of empty squares and then imagine placing numbers in consecutive squares. Subjects either read and listened, or just listened to the instructions related to the positioning of letters in the particular squares e.g. "in the first square put a 3, in the next to the right put a 1..." etc. On completion of the sequence, subjects had to verbally recall the series of sentences. In another condition, subjects were presented with a similar sequence of sentences but in this case the terms "up, down, left and right" were replaced by "good, bad, slow and quick". It was inferred that this change would interfere with the image of the matrix so that subjects would have to remember the sequence, probably via subvocal rehearsal. In the first condition, subjects recall of the position of the numbers in the matrix was higher when they listened to the instructions compared to reading and listening. No difference was found in the second or 'nonsense' condition. These data imply that reading and visual imagery share common cognitive resources and that the information manipulated in working memory is visual in nature.

In a variation of this task, Baddeley, Grant, Wight, and Thompson (1975) investigated the effects of concurrent perceptuo-motor tracking on the retention of information. Subjects listened to the sequence of sentences and simultaneously tracked a moving target. Results showed that the tracking task significantly impaired retention of the information in the imagined matrix but did not affect the retention of the nonsense information. It suggests that the retention of information in the form of a visual image involves cognitive

resources required to physically track a moving target, and by implication that *visuo-spatial* processes are required for perceptuo-motor control.

In a follow-up study, Baddeley and Lieberman (1980) used a spatial rather than a visual tracking task. Subjects were blindfolded and tracked a moving pendulum with a flashlight while they listened to the sequence of sentences. The pendulum contained a light sensitive cell and sound source that provided subjects with feedback of their tracking movements. The spatial task interfered with the retention of the matrix task compared to a nonsense sequence, but a purely visual task (brightness judgement) interfered with the nonsense sequence but not with the matrix task. Baddeley and Lieberman (1980) further demonstrated that concurrent tracking significantly interfered with a spatial mnemonic (method of loci) but not a visual (pegword) mnemonic. On the basis of these data Baddeley and Lieberman suggested that the VSSP involves spatial processes engaged in perceptuo-motor control and in the perception and manipulation of visuo-spatial information.

The suggestion that perceptuo-motor behaviour requires cognitive resources that interfere with the retention of spatial information has received further support from a number of studies by Smyth and her colleagues (Smyth, Pearson & Pendelton, 1988; Smyth & Pendelton, 1989). Smyth *et al.* (1988) compared memory span for words, body movements and pointing movements to different positions in space. In the body movement condition, subjects observed the experimenter make a series of simple movements and then reproduced them in the order of presentation. In the hand movement condition subjects performed the "Corsi blocks" task (De Renzi & Nichelli, 1975): the experimenter pointed to a sequence of blocks arranged in a random order and the subject recalled the same sequence by pointing to the blocks. Results showed a mean recall of 5 words in the verbal task, 4 items in the body movement task and 6 items in the pointing condition. During variations of these tasks subjects simultaneously performed a secondary task (articulatory suppression, hand tapping to four different positions, and

repeated arm movements). Smyth *et al.* reported that repeated arm movements during presentation interfered with the recall of the movement sequence but did not interfere with recall in the pointing task. Conversely, the hand tapping task interfered with the pointing task but did not interfere with recall of the movement sequence.

These data suggest that information of body movement is configured differently to information related to movements to targets in space, providing additional evidence that the spatial component of working memory is involved in motor control. Indeed, Quinn and Ralston (1986) were able to demonstrate that the planning of movement has a large spatial component; they showed that incompatible movements (active and passive) made without any visual feedback, interfered with information in the Brooks matrix whereas compatible movements did not result in any interference. Given the hypothesis that movement images contain the same information as action plans then the observation that action plans have a spatial component have important implications for this thesis. It suggests that attention should be focused on EEG activity recorded over cortical areas known to be involved in the processing of spatial and visual information.

These studies provide very strong evidence that dynamic imagery comprises both spatial and visual representations and although not conclusive, it also suggests separate visual and spatial processing systems. Indeed Annett (1995) suggests that the VSSP comprises 3 components: the first processes purely visual information, the second processes relative and absolute spatial information concerning an external object and the third processes movement information. The latter component is considered to be the most likely candidate for the encoding of information during observational learning (cf. Annett, 1991; Whiting and den Brinker, 1981). However, in the context of this thesis it is sufficient merely to understand that the underlying representations have spatial and visual components. It is suggested that in the case of MP, information from both systems is combined and is, therefore, visuo-spatial.

In summary, it is suggested that motor and visuo-spatial information is stored in a representational format which, when made available to conscious introspection during MP, exhibit characteristics that are similar to, or analogous with. those sensations that occur during overt movement. It is important to note that this evidence does not imply that imagery involves the *activation* of motor and perceptual representations. only that it has properties that are similar to those operating during action. The question that remains is do these representations function like their perceptual counterparts and produce similar effects on behaviour? This question has been addressed in those studies that have investigated the "functional equivalence" of imagery and perception.

2.2.3 The functional equivalence of imagery and perception

Podgorny and Shepard (1978) demonstrated that pattern recognition in the perceptual and imagery domain produce almost identical behavioural effects, i.e. they exhibit "functional equivalence". In a classic experiment, subjects were presented with a 5 x 5 square grid. In one condition they observed a letter in the grid and in a second condition they imagined a letter being formed. A probe dot was then presented somewhere in the 'empty' grid and subjects were required to indicate whether it was located on or off the letter. The complexity of the letters (shape and size), the position of the probe (presented on different parts of or at different distances from the letter) and the number of probes was varied systematically. The results showed that the response times were longer in the imagery condition but the pattern of response times for the detection of probes on imagined or perceived letters exhibited the same characteristics. These data suggest that the same pattern recognition processes are active when an object is perceived and when it is imagined. Further evidence of the functional equivalence of perceptual and imaginary processes was reported by Finke and Schmidt (1977; 1978) who demonstrated that the McCollough effect is observable in the imagery domain.

Although important in that they demonstrate the phenomenon of functional equivalence these studies examined static imagery rather than dynamic imagery. Finke (1979) investigated the effects of imagery on errors in movement that are observed subsequent to prism mediated visual adaptation. The work of Kornheiser (1976) and Welch (1978) has demonstrated that when subjects view a target object through optically displacing prisms, initial attempts to point to that target lead to consistent errors of movement, that is, they point to one side of it. As adaptation to the prisms occurs, they become more adept and are able to point to the correct position provided they have visual feedback of their errors. When the prisms are removed, subjects make pointing errors to the opposite side of the target. What is interesting is that such pointing after-effects have been found to be dependent upon the information the subject receives during adaptation. If a subject merely observes making errors during adaptation but without any feedback of their accuracy, then pointing after-effects are made only in the hand that was observed (Harris, 1965). If feedback is provided but only after the movements have been made, then pointing after-effects are made with the hand observed during adaptation and with the hand that is not observed (Welch, 1978). Finally, if subjects observe their errors and are provided with knowledge of their accuracy then pointing after-effects are partially transferred from the adapted to the unadapted hand (Wilkinson, 1971)

On the basis of these findings Finke (1979) reasoned that if imagery and perceptual processing are functionally equivalent then when subjects point to a target and imagine making errors, pointing after-effects should be observed in both hands and exhibit similar inter-manual transfer characteristics as when they actually observe themselves making errors. Furthermore, if subjects imagine making pointing errors but believe they are accurate in their movements, then pointing after-effects should only be observed in the adapted hand. To test the first hypothesis, subjects wore prisms and were allocated to either a perceptual feedback, imagery feedback or a control group. In the perceptual condition accuracy feedback was provided subsequent to the movements. In the imagery condition no accuracy feedback was provided but subjects imagined themselves making

similar pointing errors to those made and observed in the perceptual condition. No perceptual or imagined feedback was provided in the control condition. After-effects in all three conditions were assessed by subjects pointing to the target but without any visual feedback. Results showed that similar pointing after-effects were found in the perceptual and imagery conditions; the size of the effect in the imagery condition was much smaller but the amount of inter-manual transfer was proportional to that observed in the perceptual condition.

The above studies demonstrate not only the functional equivalence between visual imagery and perception but also imply that a comparable equivalence may exist between overt action and imagery of movement. Further evidence of this phenomenon was provided by Johnson (1982). It had been established in a number of studies, that recall of a previously learned movement was disrupted if a movement differing in length to the criterion movement was interpolated between learning and recall, i.e. recall was biased in the direction of the interpolated movement (Patrick, 1971). In a manipulation of this paradigm, Johnson showed that the imagination of a movement half or twice the length of a previously learned movement, interpolated between learning and recall, resulted in a similar bias in recall. Subjects tended to overshoot or undershoot depending on whether the imagined movement was greater or shorter than the criterion movement. In a further experiment Johnson (1982) was able to demonstrate that visuo-spatial representations were responsible for this bias.

It is suggested the evidence from cognitive psychology and psychophysiology support the contention that the effects of movement imagery can be explained in terms of top-down mechanisms involving motoric and visuo-spatial representations. It is also suggested that imagination of movement or mental practice has similar effects on behaviour as actual movement and, therefore, exhibit some form of functional equivalence. The implication of these arguments is that it is possible that they share common resources both at a physical and cognitive level, an idea that will be discussed further in Chapter 3.

2.3 Conclusion

In conclusion it is argued that there are a number of distinct forms of dynamic imagery, the imaginary transformation of objects and imagery of movement. It is also argued that each form of dynamic imagery involves both kinaesthetic/motoric and visuo-spatial representations, although the manner in which these representations interact during imagery varies according to a given imaginary scenario. The adoption of an external perspective involves both motor/kinaesthetic and visuo-spatial representations but the latter are hypothesised to have the greatest 'weight' in any computation. The internal perspective although involving the same type of representation might result in motor/kinaesthetic elements having most 'weight'. The assumption that dynamic imagery of movement involves both types of representation has important implications for this thesis. If it can be demonstrated that cortical areas known to active during these aspects of behaviour are also active during imagery, then it provides a valuable insight into what kind of task should be used in the following experiments and what areas of cortex should be examined.

Chapter 3

Evidence from Cognitive Neuroscience

Throughout Chapter 2 it was suggested that dynamic imagery involves motoric and visuo-spatial representations. It was further suggested that dynamic imagery maintains the structural characteristics of and is functionally equivalent with perceptuo-motor activity. That is to say, both forms of activity *share* common cognitive resources. However, the research discussed in the previous chapter is not without its critics. Pylyshyn (1973; 1981) has argued that most of the studies demonstrating the analogical nature of imagery were contaminated by subjects' tacit knowledge and task demands. Intons-Peterson (1983) has argued that most of the research related to functional equivalence of imagery and perception is contaminated by experimenter expectancy.

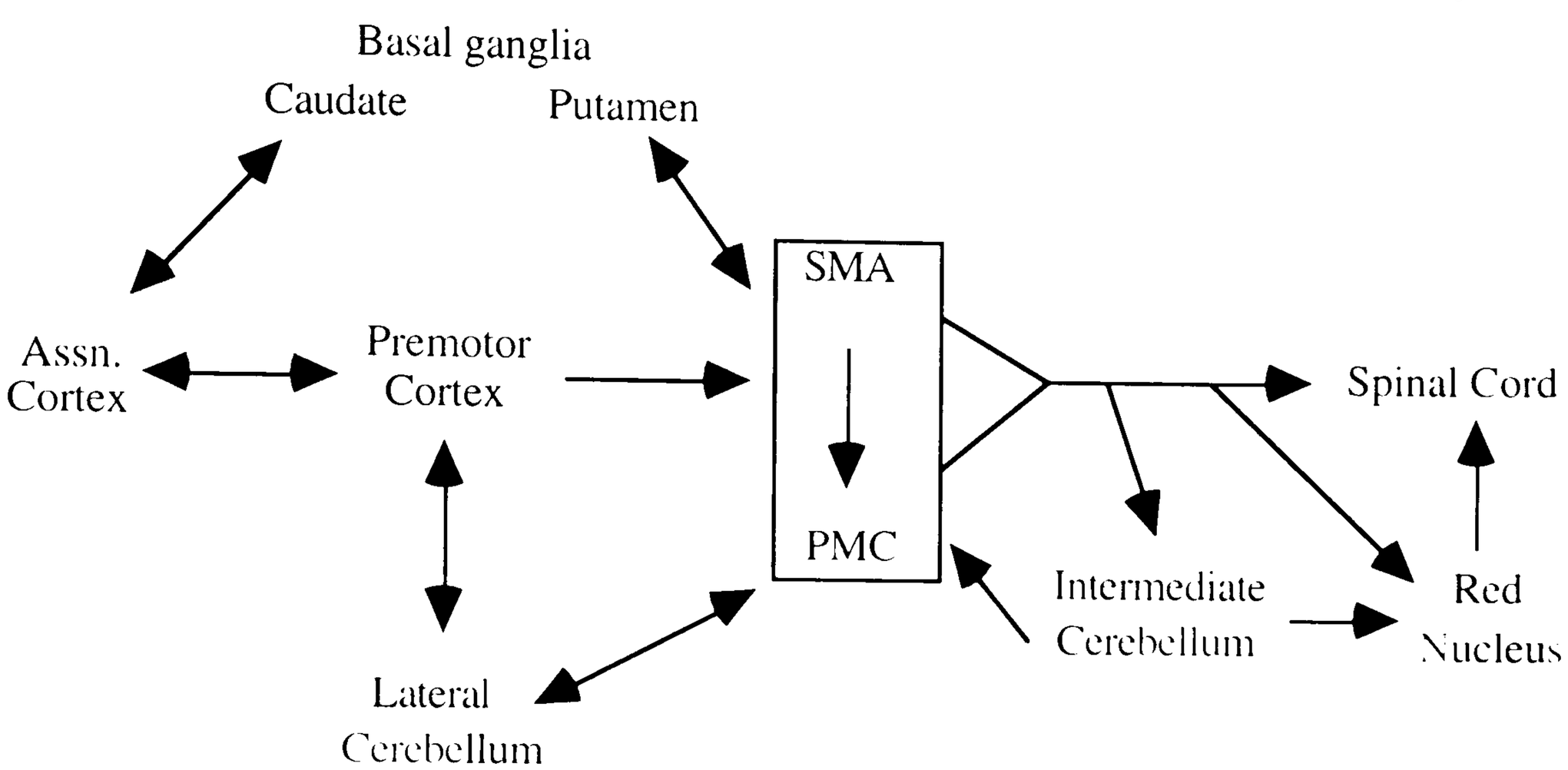
It is likely that some, but not all, of the imagery research is contaminated in the way that Pylyshyn and Intons-Peterson suggest, although it is difficult to completely rule out these alternative explanations of these data. Indeed it has been argued that no distinction can be

made between visual and non-visual theories of imagery based solely on data from cognitive psychology experiments (Anderson, 1978). It is for this reason that researchers have focused on cognitive neuroscience in an attempt to further elucidate the relationship of imagery and perception (Farah, 1988; 1989). Given this approach the main question of this thesis is simple: assuming that dynamic imagery and perceptuo-motor activity share common cognitive resources can this relationship be extended to show that they share common neural resources? If so, one would expect those areas of the cortex subserving visuo-spatial processing during perception, in addition to those involved in the planning of action, to become active during dynamic imagery. The purpose of this chapter is to outline what is known about the localisation of those processes involved in dynamic imagery as it has a direct bearing on the hypotheses proposed in this thesis. To fully understand the relevance of this research it is first necessary to gain an understanding of the anatomical connections and hierarchical organisations of the motor system.

3.1 The hierarchical organisation of motor control

Hughlings Jackson (1932) proposed that the motor system is organised in a hierarchical fashion, comprising of 'higher', 'middle' and 'lower' levels. Since then our understanding of the motor system has advanced considerably but complete understanding of its function and organisation still evades contemporary knowledge. Therefore, reference will still be made to this hierarchy as it provides a useful framework for the very simple description that is offered.

Figure 3.1 Overview of the hierarchical organisation of the motor system.



Abbreviations: Assn., association; SMA, supplementary motor area; PMC, primary motor cortex.(From Brooks 1986; after Humphrey, 1983; Allen & Tsukahara, 1974)

Any consideration of co-ordinated voluntary movement has to account for the goal of the movement, its planning and its production. Figure 3.1 shows that high level association cortex (dorsolateral pre-frontal cortex - Brodman's area 46, parietal cortex - area 5, and temporal cortex - areas 40, 39, 22 and 23) together with the caudal loop of the basal ganglia operates at the highest level of this hierarchy. It is at this level that the idea of an act is formed in response either to internal or external stimuli. The dorsolateral pre-frontal cortex (DLPFC) receives information via cortico-cortical connections from the other association areas and via sub-cortical connections from the caudate loop of the basal ganglia which possibly acts as a 'forward model' computing the hypothesised effects of particular actions on the external environment (Brown, Britain, Elvevag & Mitchell

(1994). It uses this information to plan, in the form of a motor program, a whole sequence of movements prior to its execution.

Information is then transmitted to the middle level which includes premotor cortex (medial and lateral area 6), the putamen loop of the basal ganglia and the cerebellum. It is at this level that the action plan is translated into command programs for the implementation of the action. The cerebellum is involved with both the transformation of simple fractionated movements into smooth sequential movement and with the comparison of output at the spinal level with the original goal plan. The basal ganglia plays a similar role but it compares what occurs at the premotor cortex with what was computed at the higher association cortex. The middle level integrates the relevant sensorimotor information and transmits the necessary signals via the sensorimotor cortex to the spinal cord operating at the lowest level. This implements the appropriate sub routines to innervate the relevant muscle groups.

It is important to note that the flow of information is not just in one direction as there are a number of feedback loops that compare the outcome with what was intended; corollary discharge ('efference copy') and afferent feedback are of primary importance in such a comparison. Of equal importance is the fact that a motor program is stored in a distributed manner, allowing the same movement to be made in a number of different ways. Thus, the motor system incorporates both parallel and serial processing producing a wide repertoire of flexible, complex movements.

It is hypothesised that dynamic imagery involves both motor and visuo-spatial representations. It is suggested that these motor representations are stored at the higher levels of the motor system, including the DLPFC and the SMA (medial area 6). Although the above description indicates that the SMA operates at the middle level, evidence suggests that it is crucial in the timing, pre-programming and initiation of complex movements (Eccles, 1982). Given the view that dynamic imagery and action have similar

temporal characteristics it is likely that these areas are involved in dynamic imagery. It is also suggested that visuo-spatial imagery involves cortical areas known to active during high and lower level visual processing, i.e. the primary visual cortex and posterior association areas of the cortex. This chapter discusses evidence from cognitive neuroscience which demonstrates that these areas become active during dynamic imagery.

3.2 Cortical representations of imaginary transformation

3.2.1 Effects of brain damage on imaginary transformations

Most of the research into cortical organisation of processes underlying image transformation has focused on the question of hemispheric specialisation. Given the once popular theory that the right hemisphere is specialised for the processing of imagery, and evidence that the right parietal lobe has a specialised role in the processing of spatial information, it was assumed that the right hemisphere would be dominant for image transformation (Ehrlichman & Barrett, 1983). Although this theory has been found to be an oversimplification, evidence from brain damaged patients has shown that the right hemisphere does play an important role in image transformation.

Ditunno and Mann (1990) compared mental rotation performance of patients who had focal lesions in either the right or left hemisphere. They found that patients with right hemisphere damage took longer and made more errors on Shepard and Metzler type stimuli than patients who had damage to the left hemisphere. Similar results were reported by Butters, Barton and Brody (1970) and Ratcliff (1979). More importantly, brain damaged patients in each of these studies had lesions to their right parietal lobe. In an examination of a split-brain patient, Corballis and Sergent (1988) adapted the paradigm developed by Cooper and Shepard (1973). The patient was presented with letters rotated at different angles and was required to rotate it to the upright position

before making an assessment as to whether it was normal or mirror-reversed. Results showed that the patient was faster and more accurate when the stimuli were presented to the left visual field (right hemisphere).

As discussed by Ehrlichman and Barrett (1982), the hypothesis of right hemisphere specialisation for imaginary transformations is an over-simplification, and it is likely that the left hemisphere is also involved. Mehta, Newcombe and Damasio (1987) examined the performance of patients with damage either to their left and right hemisphere on a number of tasks, including mental rotation. They reported that, in comparison to a control group, patients with lesions of the left hemisphere were significantly impaired on the mental rotation task. Mehta and Newcombe (1992) also showed that patients with left hemisphere damage were significantly impaired in two tests involving the imaginary transformation of 3D objects. LeDoux, Wilson and Gazziniga (1977) described a split-brain patient who was unable to perform tasks thought to engage transformation processes, with his left hemisphere. Similar evidence has been reported by De Renzi and Faglioni (1967), Kim, Morrow, Passafiume and Boller (1984). It seems likely that image transformation involves both hemispheres.

The results reported by Kim *et al.* (1984) are important as they also provide some insight into the role of motoric processes in imaginary transformations. In this study, performance of 4 groups of patients with damage to either the left anterior, left posterior, right anterior or right posterior hemisphere, was compared on five visuo-perceptual and five comparable visuo-motor tasks. Results showed that patients with right hemisphere damage performed worse than patients with damage to the left hemisphere. Furthermore, performance of patients with right posterior damage was worse than those with right anterior damage, whereas patients with left anterior damage performed worse than patients with left posterior damage. What is important in this study is that left anterior damage resulted in poorer performance compared to right anterior damage on tasks that involved mental rotation. The frontal lobes have been implicated in the planning of motor

commands and in "higher forms of attention", (Luria, 1973) so these data could be interpreted as showing not only that motor processes are involved in image transformation, but that the relevant motoric representations are lateralised to the left hemisphere. This would make sense given the critical role in motor programming assigned to the left hemisphere (Kimura, 1977).

In a study of unilateral Parkinson's Disease (PD) patients, Dominey, Decety, Broussolle, Chazot and Jeannerod (1995) also made an assessment of their mental rotation ability, using letters or hand drawings (right and left). Results showed that hands were rotated slower than letters in both groups, that reaction time increased linearly with the degree of rotation and that the PD group were slower than the controls using both types of stimuli. Furthermore, the PD were significantly slower at rotating a drawing of their affected hand. These data then, provide further evidence for the involvement of motoric processes in image transformation.

3.2.2 Psychophysiological studies of image transformation

Early psychophysiological investigations of mental rotation also focused on hemispheric specialisation. In an EEG study, Furst (1976) found that alpha power decreased over the right parieto-occipital cortex of the right hemisphere during performance of the Shepard and Metzler (1971) mental rotation task. In a study which examined a number of spatial tasks including mental rotation, Ornstein, Johnson, Herron, and Swencionis (1980) found that differences in hemispheric activation were dependent on the type of task. For example, performance of modified versions of the Nebes arc-circle and circle-circle matching task, activated the left and right hemisphere respectively, whereas an adapted version of the Shepard and Metzler (1971) mental rotation test primarily activated the left hemisphere. The locus of activation in these tasks was over the parietal regions of each hemisphere.

In a number of studies that used the BEAM technique to investigate cortical changes during mental rotation, Rappelsberger and his colleagues (e.g. Rappelsberger & Petsche, 1988; Rappelsberger, Krieglsteiner, Mayerweg, Petche & Pockberger, 1987) observed a bilateral decrease in absolute power over the parietal region in both the alpha and beta 1 frequency bands. However, beta 2 power increased during this task. These studies are important as they demonstrate that different frequencies index different task specific information. However, they must be treated with caution as no inferential statistics were performed and so they can only be used to describe characteristics of these data. It is suggested that these data are consistent with those obtained in studies that have examined brain damaged and normal subjects (e.g. Jones & Anuza, 1982). That is, they demonstrate that mental rotation involves the parietal regions of both hemispheres.

A number of studies have used the ERP paradigm to investigate specific sub-processes involved in the solving of a mental rotation problem. Peronnet and Farah (1989) recorded ERPs from midline electrodes during the performance of a task developed by Cooper and Shepard (1973); letters were presented either normally or mirror reversed and were tilted to vary the angular disparity of the figure from the upright position. Subjects were required to rotate the figure to the upright and then decide whether it was normal or mirror reversed. Results showed an increased negativity over the parietal cortex at a latency that was interpreted as reflecting the rotation process. Furthermore, a relationship between the amount of negativity and the degree of rotation was also observed.

Similar results were found in study which compared shifts in DC potentials during mental rotation and arithmetic tasks (Rosler, Schumacher & Sojka, 1990). Rosler *et al.* (1990) found that changes in the EEG were dependent on the type of task and of the level of difficulty. More specifically, they found an increase in positivity (indicative of a state of inactivity) over the anterior region of either hemisphere during arithmetic, the amplitude of which increased in line with the complexity of the problems. Mental rotation of letters, however, resulted in increased negativity (indicative of neural

activation) over the central parietal cortex as the angular disparity of the two images increased. Furthermore, the decision of whether the two images are identical or mirror images produced an increase in negativity at a latency that was later than that associated with the rotation process. Further evidence of this relationship was provided by Rosler, Heil, Bajric, Pauls, and Hennighausen (1995) who were also able to demonstrate that potentials separate from the P300 component reflected these changes. Michel, Kaufman, and Williamson (1995) also reported similar findings using both EEG and magnetoencephalographic techniques.

Studies of neural activation using rCBF techniques are less common than those that employ the EEG. A study by Deutsch, Bourbon, Papanicolaou and Eisenberg (1988) using ^{133}Xe has important implications for the hypotheses set out in this thesis. In this study, increased activation was observed over the parietal, occipital and frontal cortex, during performance of Shepard and Metzler's mental rotation task. Activation was greatest over the right hemisphere at each of these locations i.e. it demonstrated an asymmetry in frontal activity that was contrary to that reported by Kim *et al.* (1984). Charlot, Tzuorio, Zilbovicius, Mazoyer and Denis (1992) also provided evidence of parietal activation during tasks thought to engage dynamic imagery processing. The results of these studies suggest both, that cortical regions known to subserve visuo-motor processing and the planning of movement are active during the active transformation of images, and that the right hemisphere is crucial in such activity.

There is a general consensus that the parietal cortex has a primary role in imaginary transformations. Studies using rCBF methods have also demonstrated that the anterior region of cortex is also active though similar evidence has not been reported by electrophysiological studies. This may be due to the fact that most EEG studies did not examine activity over pre-frontal regions of cortex. Taken together the evidence suggests that imaginary transformations engage both motoric and visuo-spatial representations.

3.3 Cortical representations of visual imagery

3.3.1 Effects of brain damage on visual imagery

If one assumes that visual imagery and perception share common neural mechanisms, it follows that damage to areas of the brain known to be involved in the processing of visual information produce deficits in visual imagery. Furthermore, given the evidence that individual components of the visual system appear to be specialised for particular functions, damage to a given area should result in similar deficits in perception and imagery. One of the best examples of the loss of imagery function associated with brain damage was reported by Bisiach and Luzzatti (1978) who described case studies of two patients with hemispatial neglect for visual information following damage to their right parietal lobes. They were asked to imagine and then describe Milan's Piazza del Duomo from two different perspectives. When they imagined the square from one view they omitted many of the landmarks from the left side of the imagined scene. When they imagined it from the opposite view they again neglected the left side of the image, describing many of the landmarks they had previously omitted.

Similar deficits were reported in 3 patients who exhibited unilateral neglect following damage to the right parietal lobe (Meador, Loring, Bowers & Heilman, 1987). All three patients neglected objects in the left visual field during both perception and imagery. When one of the patients was instructed to move his head or eyes to the left during imagery performance, he showed an increased ability to 'visualise' objects in that side of the imagined visual field. Kosslyn (1994) interprets these two sets of data as providing support for the idea that the anticipation of visual events primes stored representations of objects, thereby facilitating the generation of and selective attention to visual images in the visual buffer.

Given Kosslyn's suggestion that this anticipatory mechanism is programmed by the motor system, the implication of his interpretation here is that visual neglect may be a consequence of perceptuo-motor deficits rather than pure perceptual deficits. This makes sense given the role of the parietal lobe in visually guided movement (Kalaska & Crammond, 1992; Taira, Mine, Georgopoulos, Murata & Sakata, 1990) and the neural connections between parietal regions and motor regions of the frontal lobes (Fellerman & Van Essen, 1991).

Farah, Soso and Dashieff (1992) used a technique developed by Kosslyn (1978) to determine the visual angle of an image, in a case study of a patient with homonymous hemianopia before and after she underwent unilateral occipital lobe resection for the treatment for epilepsy. Following surgery it was found that the horizontal dimension of her imaginary visual field was reduced, a deficit which mirrored the change in the size of her visual field. Such evidence suggests that representations used during imagery are located in the occipital lobes.

Further support for the role of visuo-spatial cortical areas in imagery has been reported by Levine, Warach and Farah (1985). Levine *et al.* demonstrated that two patients with damage to different cortical areas known to be involved in the recognition and location of objects, showed dissociations in imagery tasks that mirrored their visual abilities. Case 1 (bilateral occipital damage) was able both to name objects he perceived and describe objects from memory, but was unable to localise visual stimuli in space or describe the position of familiar objects from memory. Case 2 (bilateral inferior temporal) had object agnosia and was unable to describe objects from memory but was efficient at localising visual stimuli and at describing their position from memory. In a more detailed examination of the cognitive deficits of case 2, Farah, Hammond, Levine and Calvanio (1988) showed that this patient was impaired on tasks involving purely visual processing of information, but performed normally on tasks requiring spatial processing. The authors

interpret these findings as providing, on the one hand, evidence that imagery and perception share common neural resources, and on the other as showing that different cortical areas subserve different components (visual and spatial) of imagery.

Evidence of an association between loss of colour imagery and colour perception (Beavois & Saillant, 1985; Riddoch & Humphrey, 1987; Sacks & Wasserman, 1987), between face imagery and face recognition (Shuttleworth, Syring & Allen, 1982) and between imagery and object recognition abilities (Beyn & Knyazeva, 1962) add strong support for the claim that imagery representations involve visual cortical areas. This is not to say, however, that all patients with damage to the visual areas of the cortex exhibit such deficits in imagery ability. Jankowiak, Kinsbourne, Shalev and Bachman (1992) and Behrmann, Winocur and Moscovitch (1992) reported on two agnosic patients whose imagery abilities were left intact. In contrast Charcot and Bernard (1883) reported a case of a patient who displayed normal visual perception but exhibited complete loss of visual imagery.

Kosslyn (1994) has proposed that although identical, the mechanisms subserving imagery and perception may be used differently in each case. During imagery, stored percepts with semantic content are generated from long term memory; during perception, visual information is processed and then matched to stored representations. Therefore he argues that damage to the latter processes can result in perceptual impairment without affecting imagery. Even if Kosslyn's arguments are found to be incorrect, it must be said that such cases are rare and in no way undermine the evidence demonstrating that imagery and perception share some common neural mechanisms.

3.3.2 Psychophysiological studies of visual imagery

A number of different techniques have been used to investigate the neural correlates of dynamic imagery. These can be divided into studies that have examined the electrical activity of the cortex (Brain Electrical Activity Mapping - BEAM, the electroencephalogram - EEG, event-related potentials - ERPs and magnetoencephalogram - MEG) and those studies that have examined brain activity based on regional cerebral blood flow (positron emission tomography - PET, single photon emission computed tomography - SPECT, and functional magnetic resonance imagery - FMRI). The relative strengths and weaknesses of each of these techniques are discussed in chapter 5.

Most studies that have used the EEG have tended to focus on the alpha frequency (8-13 Hz), a common assumption being that the absolute power (μV^2) in this frequency band is inversely related to brain activity, that is to say, a decrease in alpha power (alpha suppression) is associated with increased neural activity (Shagass, 1972). A number of early studies investigating the relationship between EEG and visual imagery are based on this assumption and all observed a decrease in alpha over the occipital areas of the cortex (Barratt, 1956; Brown, 1966; Golla, Hutton & Walter, 1943; Short, 1953; Slatter, 1960; Walter & Yeager, 1956). However, other studies have failed to observe this phenomenon (Drever, 1955, 1958; Oswald, 1957; Mundy-Castle, 1957).

It is suggested that the conflict of opinion found in these early studies of visual imagery stems from the great variation in the tasks used in these experiments. Most of them provided only very indirect assessment of imagery (e.g. Walter & Yeager (1956) assessed the vividness of the 10 images in a post experimental interview). In other studies some of the tasks were very general (e.g. in the study of Golla *et al.* (1943), subjects were asked to " 'see' some person or place they knew well."). Further criticism levelled against the results of these early studies is that alpha suppression over the occipital cortex could have

been a result of variation in task difficulty and the level of general 'arousal' elicited during the tasks (Oswald, 1957).

A study which did control for task difficulty was reported by Davidson and Schwartz (1977) who recorded the EEG from occipital and parietal areas of the cortex during visual (imagine a flashing light) kinaesthetic (imagine the arm being tapped) and visuo-kinaesthetic imagery (imagine a combination of the two). Alpha suppression was greatest over occipital cortex during the visual imagery task and over the parietal cortex during the kinaesthetic imagery task. Furthermore, the combination of visual and kinaesthetic imagery resulted in an equal distribution of alpha over the occipital and parietal areas. The results of this study have important implications for the distinction between the internal/external perspective discussed in this thesis; it suggests that the separate 'modules' thought to comprise these different forms of imagery have a different topographic organisation.

The study of Davidson and Schwartz (1977) is typical of most EEG investigations of imagery, in that it examines hemispheric differences in EEG. A number of studies claimed to demonstrate that the left hemisphere is specialised for processing of verbal/analytical material whereas the right hemisphere is specialised for the processing of visual images (Morgan, McDonald & MacDonald, 1971; Ehrlichman & Wiener, 1980; Robbins & McAdam, 1974). However, Ehrlichman and Barrett (1982) argued that these studies do not allow any differentiation of role of the two hemispheres in such tasks. For example, they argue that the data reported by Morgan *et al.* (1971) demonstrated that verbal/analytical but not imagery processes are lateralised; there was no difference in alpha power between a baseline and imagery condition and the hemispheric ratio score for these conditions was almost identical. Evidence supporting the contention of bilateral activation during imagery has been reported by Barrett and Ehrlichman (1982) and Haynes and Moore (1981) who found no difference in hemispheric activation during

visual imagery. The question of hemispheric specialisation aside, these studies do demonstrate that visual imagery results in alpha suppression over posterior regions of the cortex, thereby providing evidence to support the contention that visual imagery and perception share common neural resources.

In a study using the ERP technique Farah, Peronnet, Gonon and Giard (1988) repeated the paradigm used by Farah (1985) to investigate the interaction of imagery and perceptual processes. Cortical activity was recorded during an imagery task, imaging an H or a T while being visually presented with either letter or no letter. The results reported by Farah (1985) were again observed (the detection of a letter in a perceptual task was greatly facilitated by generating an image of that same letter compared to a different letter). An examination of the electrophysiological data showed a significant difference in the amplitude of the early negative components (below 200 ms) of the EEG recorded during the matching and non matching imagery conditions. Moreover, this difference was maximal at occipital sites. The importance of this finding is that these early negative components have their origins in areas 18 and 19 of the cortex (Lesevre & Joseph, 1979; Maier, Dagnelie, Spekreijse & Van Dijk, 1987) which are active during relatively early stages of the processing of visual information. These data then, show not only that imagery has a content specific interaction with perceptual processes, but that the locus of this interaction is over modality specific visual cortex.

Farah, Peronnet, Weisberg, and Monheit (1989) provided further evidence that the occipital areas are active during the generation component of imagery. They recorded ERPs when subjects either just read words or read words and generated an image of their referents. An additional baseline of reading abstract words was also included to control for a failure to comply with the instruction of reading the word without forming an image of its referent. They found no difference between the conditions during the first 450 ms of processing (reflecting the reading component common to both conditions) but observed a

significantly greater positivity at occipital sites in the later components during the imagery condition compared to the other conditions. This was interpreted as reflecting imagery processing in the visual cortex.

Roland and Friberg (1985) measured rCBF of subjects during a number of tasks including the visualisation of a walk through their neighbourhood. Results showed that in comparison to a baseline, rCBF significantly increased in posterior regions of the cortex. The greatest increase was observed over the posterior superior parietal cortex reflecting the large spatial component of the task (subjects were required to take alternate turns to the right and left during the imagined walk). Significant increases were also observed in the posterior inferior temporal and superior occipital cortex reflecting the importance of posterior association areas in such tasks.

In a SPECT study, Goldenberg, Podreka, Steiner and Willmes (1987) required subjects to learn concrete and abstract words either through rote learning or through the use of a mnemonic strategy. They reported an increase in rCBF in the occipital area of cortex bilaterally and greater activation in the left inferior occipital cortex. Goldenberg, Podreka, Steiner, Willmes, Suess and Deeke (1989) produced similar results using SPECT in a study that required imagery to evaluate the correctness of high imagery statements (e.g. "A frog has a long tail"). In line with the arguments put forward by Farah (1984; 1985; 1988), Goldenberg and his colleagues have suggested that the locus for the image generation component in the left posterior region of the cortex. This interpretation is not without its critics. Sergent (1990) has refuted the conclusions of Farah (1984) and suggests that only 1 of the 14 case studies reviewed by Farah to support her conclusions actually support the hypothesis. Furthermore she points out that in Goldenberg's studies the occipital and temporal lobes were activated *bilaterally*, thereby demonstrating that the right hemisphere may also be involved in image generation.

The question of hemispheric specialisation in visual imagery does not detract from the evidence that areas of cortex involved in the processing of perceptual information also become active during visual imagery. Indeed, more recent studies using techniques with superior spatial resolution than that adopted by Farah and Goldenberg and his colleagues. have provided evidence that activation of visual cortex may be dependent upon specific sub-processes. Kosslyn, Alpert, Thompson, Malijkovic, Weise, Chabris, Hamilton, Rauch and Buonanno (1993) demonstrated that the primary visual cortex (area 17) was active during an image generation task adapted from the Podgorny and Shepard (1978) study (cf. Farah *et al.*, 1988). On the basis of these data they suggest that visual information is stored in visual association cortex and is back projected via top-down processes to the primary visual cortex. As this area is retinotopically organised it suggests that the internal structure of a percept is maintained in an image. The Podgorny and Shepard (1978) study provides some of the strongest evidence of functional equivalence of imagery and perception, so the results reported by Kosslyn *et al.* are particularly important as they demonstrate that this relationship extends to the cortical level.

In summary, it is suggested that there is strong evidence to support the hypothesis that visual imagery activates areas of the cortex that are involved in the processing of visual information. As it is assumed that movement imagery comprises both motor and visuo-spatial representations, then attention should be focused on the primary and association visual cortex during any experiments that address this issue.

3.4 Cortical representations of movement imagery

3.4.1 Effects of brain damage on imagery of Movement

If damage to neural areas known to be involved in perception produce comparable deficits in visual imagery and visual perception, implying that they share common neural substrates, then this kind of reasoning may be extended to imagery of movement. If

similar deficits in overt action and imagery of movement are observed following damage to neural areas known to be involved in the planning of movement, then it may be suggested that the same neural mechanisms are involved in both types of types of activity.

Evidence that neural damage produces similar behavioural effects during overt action and imagery of action has been reported by Decety and Boisson (1990). Right handed patients with hemiplegia (right and left), tetraplegia or quadraplegia imagined and attempted to perform a number of tasks; sign their name, draw a Necker cube and hop on one leg (the third task was of course only performed mentally). An examination of the time taken to imagine signing their name showed that the hemiplegic patients took longer with their affected limb. However, the tetraplegic and quadriplegic patients were slower with their non-dominant hand. Similar results were obtained in the hopping task; duration of movement imagery was longer with the affected leg in the hemiplegic patients, while the duration of mental movement in the tetraplegic and paraplegic patients was greater when they used the non-dominant leg. These results show that imagery characteristics of patients with damage to high levels of the neuro-axis (hemiplegics) paralleled their deficits in motor control. In contrast, the temporal characteristics of movement and images of movement in those patients who incurred damage at a more peripheral level were similar to normal subjects. The results clearly suggest that damage to the motor system has equivalent effects on the imagery of movement, implying that they share common neural resources.

Ochipa, Rapcsak, Maher, Bowers, Gonzalez-Rothi and Heilman (1991) reported a clinical case of a patient with severe ideomotor apraxia. This patient not only made spatial and movement errors during physical assessment, but was also unable to provide answers to questions about the spatial position of his hands or about the movement of particular joints (i.e., the patient had to generate appropriate motor imagery to answer the

questions). These parallel deficits in action and imagery show that similar representations are used both for gestures and during imagery of movement (cf. Annett 1986; 1990).

In the study of Dominey *et al.* (1995) parallel deficits in motor imagery and overt action were found in unilateral PD patients. Patients performed a sequential finger movement task with each hand under three separate conditions; with or without visual feedback or during movement imagery. Results showed that the PD patients performed each of the tasks at a slower rate than a matched control group and that they performed quickest in the visually guided condition and slowest in the imagery condition. More importantly, compared to the control group, performance in the PD group was slower with their affected hand in all three conditions. It was also reported that one patient who exhibited levodopa-induced periods of being "on" or "off", was unable to perform or imagine performing the finger sequence during an "off" period. However, subsequent to medication and the return to an "on" state, the patient was able both to produce and to imagine the sequence.

Given the evidence of bilateral activation of the basal ganglia during sequential finger movements (Roland, Meyer, Shibasaki, Yamamoto & Thompson, 1982) and reduced activity in the putamen contralateral to the affected limb in unilateral PD (Benecke, Rothwell, Dick, Day, & Marsden, 1987; Leenders, Palmer, Quinn, Clark, Firnau, Garnett, Nahmias, Jones & Marsden, 1986; Nahmias, Garnett, Firnau & Lang, 1985) these findings suggest that the basal ganglia and by implication the fronto-striatal system are also involved in the planning of action and during motor imagery.

It is also interesting to note that patients in all three studies did not exhibit any deficits in performance of visual imagery tasks. This suggests that specific damage to motor representations rather than damage to mental imagery *per se*, was responsible for the observed deficits in motor imagery. These results provide clear evidence that damage to high level motor structures produces comparable deficits in both overt action and in

motor imagery and by implication suggests that imagery of movement involves the motor system proper. They also suggest that visuo-spatial and motor imagery are independent 'modules'.

Other studies have reported that motor imagery remains intact in PD patients. Annett and Smith (1988) examined the ability of patients with moderately severe PD to physically tie or mentally simulate tying a bow. Compared to an aged matched control group, the PD patients took 3 times as long to physically tie the bow but when asked to provide a verbal description of the task their qualitative report was better and took less time than the controls. Schnider, Gutbrod and Hess (1995) also reported intact motion imagery in PD patients. Although there are inconsistencies in these data, the research described above provides strong evidence that in some cases, damage to neural motor structures produce equivalent behavioural deficits during overt action and motor imagery.

3.4.2 Psychophysiological studies of movement imagery

There have been very few electrophysiology studies that have examined movement imagery, a result perhaps of the inherent problems this technique presents when examining movement *per se*. Breitling, Guenther & Rondot (1986) used BEAM to examine changes in different EEG frequency bands associated with the physical production or imagination of a finger apposition task. They found that in comparison to a baseline condition, alpha amplitude recorded during movement imagery decreased over the primary motor cortex bilaterally and over the central and right pre-frontal region. Furthermore, activity in the beta 2 frequency decreased over the central and right pre-frontal region and over the ipsilateral motor cortex. These results were interpreted as showing that motor areas of the cortex are involved in the imagination of a complex series of movements. Ivanova and Artemova (cited in Breitling *et al.*, 1986) also found a decrease in alpha amplitude over the contralateral rolandic area during the imagination of unilateral hand movements.

Beyer *et al.* (1990) examined activity of the autonomic and central nervous system of elite performers during the imagination of their particular sport (wrestling). Results showed that alpha amplitude around 10 Hz increased over pre-central and occipital cortex during motor imagery, although there is insufficient detail provided in the paper to determine whether EEG was recorded over pre-frontal or Rolandic areas of the cortex. This study is important as it produced evidence that is contrary to the well established hypothesis that a decrease in alpha reflects increased neural activation. It is possible then, that absolute power within a frequency band increases during certain forms of cognitive processing, i.e. during movement imagery.

In a more recent study that examined DC potentials in the EEG (Beisteiner, Hollinger, Lindinger, Lang & Berthoz, 1995), subjects were required either to produce a sequence of movements using a joystick or to imagine making the sequence. Results showed that in comparison to a baseline, neural activity increased over the primary motor cortex, contralateral to the hand used in both the physical and imagery conditions. The authors interpret these data as demonstrating that the primary motor cortex is involved in motor imagery. The increase in neural activity recorded over this area are somewhat suprising given the evidence from cerebral blood flow studies. However, electrophysiological techniques have relatively poor spatial resolution, so it is possible that although the site of these observed changes were situated over the primary motor cortex, activity generated by other neural motor structures (SMA) may have contributed to the signal. Nonetheless, these studies clearly demonstrate that the motor system is active during imagery of movement.

More detailed investigations of the neural structures involved in movement imagery have used cerebral blood flow techniques. The most influential paper in this area was reported by Roland, Larsen, Lassen and Skinhoj (1980). Roland *et. al* (1980) found that performance of a finger apposition task led to an increase in activation in the contralateral primary motor cortex and the supplementary motor area (SMA) bilaterally. The

imagination of the same task, however, produced bilateral activation of the SMA but the primary motor cortex remained silent. Furthermore, in a comparatively simple physical task they found no activation of the SMA . Roland *et al.* interpreted these data as showing that the SMA is involved in the planning or pre-programming of a complex series of movements and, therefore, operates at a relatively high level in the hierarchical organisation of motor control.

This interpretation was criticised by Fox, Fox, Raichle, and Burde (1985) who suggested that the data of Roland *et al.* could have been due to differences in task performance rate. Fox *et al.*(1985) found that the SMA became active during performance of simple finger movements that were paced at a fixed rate. Colebatch, Deiber, Passingham, Friston, and Frakowiak (1991) also found that the SMA and lateral pre-motor areas become active during a simple and complex series of finger movements performed at a fixed rate. As pointed out by Rao, Binder, Bandettini, Hammeke, Yetzin, Jesmanowicz, Lisk, Morris, Meuller, Estkowski, Wong, Haughton and Hyde (1993), the tasks used in these studies were different and varied in complexity compared to those used in the Roland *et al.* study. In addition, movements in the studies of Fox *et al.* (1985) and Colebatch *et al.* (1991) were paced by an external mechanism which might have required greater neural computation compared to the self paced movements made in the study of Roland *et al.* (1980).

In a study that used FMRI technology, Rao *et al.* (1993) required subjects to make simple and complex series of movements with either hand. In a further two conditions subjects either performed the movements at a fixed rate or they imagined making the complex series of movements. During the simple self paced task they observed an increase in activity in the contralateral primary motor cortex. During the complex self paced task they found an increase in activity in the primary motor cortex and lateral premotor cortex bilaterally, and also in the SMA. The fixed rate movements produced similar results but there was less activation due to the relative slowness of the movements. More

importantly, movement imagery also produced an increase in activation in the SMA and the premotor cortex. This study replicated the findings of Roland *et al.* (1980) and adds support for the hierarchical organisation of the motor system and for the role of the SMA in the imagination of complex movements. Further evidence supporting this hypothesis has been reported by Stephan, Fink, Frith, and Frackowiak (1993) and Decety, Sjoholm, Ryding, Stenberg and Ingvar (1990).

An earlier study by Ingvar and Philipson (1977) found that unilateral hand movements produced an increase in rCBF over the frontal lobes and over contralateral primary motor cortex. During the imagination of the same sequence, however, an increase in rCBF was found only in the frontal lobe, though this technique did not allow the differentiation of the SMA and the pre-frontal cortex. The findings of this study were later replicated by Decety *et al.* (1990) who demonstrated that both the SMA and the cerebellum were active during movement imagery. More recently, Decety, Perani, Jeannerod, Bettinardi, Tadary, Woods, Mazziotta and Fazio (1994) also reported evidence of activity in sub-cortical motor structures during movement imagery.

In this PET study using the $H_2{}^{15}O$ technique, rCBF was recorded during 3 conditions: observation of movement, movement imagery and visual inspection (control). In the observation condition subjects observed a virtual hand "as if it were their own" whereas in the movement imagery condition they were instructed to imagine grasping a virtual object. In the control condition subjects merely had to inspect virtual objects. Results showed that during observation of their virtual hand, areas exhibiting greatest activation included inferior parietal and inferior temporal cortex, both of which are known to be involved in the processing of visual motion. Observation of movement also resulted in the activation of the basal ganglia of the left hemisphere, and bilateral activation of the cerebellum. During movement imagery lateral premotor areas of the cortex were activated bilaterally and pre-frontal areas (including the dorsolateral frontal cortex) contralaterally to the imagined hand (cf. Fox, Pardo, Petersen & Raichle, 1987). In

addition, the basal ganglia (caudate nuclei) were active bilaterally, though only the contralateral cerebellum was active.

These studies are important as they clearly demonstrate that cortical and sub-cortical structures known to be involved in motor control also become active during movement imagery. The role of the SMA in the planning and programming is well documented and more recent research has shown that the pre-frontal cortex is also crucial for the generation of willed, purposive action (Frith, Friston, Liddle & Frackowiak, 1991). Though the exact role of the basal ganglia remains elusive, parts of this complex (the caudate loop) are considered to operate at a high level in motor control and is hypothesised to be crucial for the computation of a feedforward model (Brown *et al.*, 1994). Seitz and Roland (1992) were able to show that the learning of complex sequence of finger movements with the right hand, (cf. Roland *et al.*, 1980) was characterised by specific changes in the left putamen and globus pallidus. In a study which examined rCBF during 3 different stages of learning in a finger apposition task, Seitz and Roland showed that activity in these nuclei increased as subjects became more proficient. Conversely, rCBF in the superior parietal (bilaterally) and right inferior frontal cortex decreased during learning. This study also showed that the right cerebellum was active during the production of a finger apposition task, as did Wessel, Zeffiro, Lou, Toro and Hallett (1995), using $H_2{}^{15}O$. The fact that all of these neural structures are active both during overt action and motor imagery provides strong evidence to support the hypothesis that imagery of movement involves the motor system and those areas of association cortex known to be involved in visuo-motor processing.

3.5 Conclusion

In summary, it is suggested that although there are inconsistencies in studies using electrophysiological and rCBF methods, taken together they provide strong evidence supporting the hypothesis that motor imagery activates areas of the cortex that are

involved in the processing of visuo-motor information. As rCBF methodology has superior spatial resolution compared to the EEG and given the problem of localising the source of the EEG signal, it is argued that the rCBF method provides more accurate information of those cortical areas involved in movement imagery. It is hypothesised that the DLPFC and the SMA become active rather than the primary motor cortex during movement imagery, reflecting their role in the planning and organisation of action plans. Thus, attention should be focused on these cortical areas during any experiments that examine this form of mental activity.

The research reviewed in this chapter provides strong evidence for the hypothesis that dynamic imagery (imagery of movement and imaginary transformations) involve neural structures thought to be important in the planning and production of purposive visuo-motor behaviour. However, there are a number of caveats to this argument. First, there are weaknesses in all of the neuro-imaging techniques described in this chapter and so one must be careful in how such data are interpreted. Second, most of the tasks employed in these studies related to movement imagery are very simple and involve only hand movements, a result of the limitations on experimental design imposed by modern neuro-imaging techniques. Caution must be exercised when extrapolating such data to other forms of movement and imagery of movement. Third, the use of data from brain damaged patients as a means of explaining normal cognitive processing is also fraught with difficulties. For example, it is extremely difficult to control for the size and effects of individual lesions so caution should be exercised when interpreting such data in isolation of other evidence.

It is suggested that despite the weaknesses inherent to each of these approaches, it is important to take note of converging evidence from each of the techniques. If one adopts this kind of reasoning, then there is powerful experimental evidence suggesting that dynamic imagery shares neural representations involved in visuo-motor behaviour.

Chapter 4

Individual Differences in Imagery Ability

In the previous two chapters a considerable amount of evidence was presented to support the hypothesis that dynamic imagery shares cognitive resources with motor and sensory systems. It was further suggested that this sharing of resources can be extended to the physical domain, as neural structures known to be involved in perceptuo-motor behaviour are also active during dynamic imagery. It is important to note, however, that all of these findings may be subject to individual variation in imagery abilities.

It is probably true to say that research into the role of imagery actually began with investigations of individual differences (Galton, 1880, 1883) and this topic continues to be an important dimension of imagery research. It is also true to say that research into individual differences in imagery ability remains a contentious issue and arouses

considerable debate. At the present time there are many questions being asked, though very few clear answers have been forthcoming.

4.1 Assessment of Individual Differences in Imagery Ability

Individual differences in imagery ability has been investigated through three main types of assessment. The first method is the use of subjective questionnaires which assess the use of imagery by individuals in a variety of different settings, often taking into account the preferred imagery modality of the respondents. The second is the use of questionnaires which provide a self report assessment (usually in the form of a rating scale) of a number of different characteristics of images; these include their vividness, the ease with which they can be controlled and manipulated, and whether visual or verbal processing is the preferred mode of thought. The third approach is the use of tests which are assumed to involve imaginal processes for the successful completion of any given task. The latter is assumed by many to be superior to the first two techniques as it provides objective evidence of the use of imagery. However, it must be said that each of these techniques provide important information regarding individual differences, although they all have inherent weaknesses.

4.1.1 'Use of Imagery' Questionnaires

Examples of this type of measure include the Imaginal Processes Inventory (IPI) (Singer & Antrobus, 1972), the Imagery Use Questionnaire (IUQ) (Hall, Rogers & Barr, 1990), the Psychological Skills Inventory for Sports (PSIS) (Mahoney, Gabriel & Perkins, 1987) and the Individual Differences Questionnaire (IDQ) (Paivio & Harshman, 1983). The IUQ (Hall *et al.*, 1990) comprises 37 items which among other things gauges the frequency with which athletes use imagery, the preferred modality and its relationship to competition performance. For 35 of the items respondents are required to rate their response on a scale of 1 to 7 (e.g. 1 = never to 7 = always). The IUQ was used in a study

which investigated the use of imagery in athletes with variable levels of skill. taken form 6 different sporting domains classified as comprising either 'open' or closed skills (Hall, Rogers & Barr, 1990). The results showed that elite athletes used imagery more than their less accomplished counterparts and that they use imagery procedures in a more controlled and systematic fashion. It was also found that an internal perspective was the favoured mode in athletes who engaged in sports that involved 'closed' skills.

The PSIS (Mahoney *et al.*, 1987) is a 51 item questionnaire which investigates a number of key variables thought to be related to athletic performance. These range from the measurement of anxiety to the assessment of use of mental imagery (particularly with regard to the external and internal perspective). Subjects answer 'true' or 'false' to each item which although having the benefit of simplifying the answers and increases the speed of administration results in valuable information being lost. It also imposes severe restrictions on statistical analysis and only produces descriptive data.

This type of questionnaire does provide useful information regarding the use of imagery and its relation to sporting performance. Its main limitation is that it does not allow any real inferences to be drawn about *why* imagery is useful. Furthermore, although it addresses important issues like the adoption of different perspectives during imagery, it provides no insight of how individual differences may be related to specific representations involved in these different types of imagery.

4.1.2 Self Report Questionnaires

This type of questionnaire has been the most widely used instrument in assessing individual differences in imagery ability, most of which have addressed the vividness or clarity of an evoked image. This instrument has its roots in the "breakfast table questionnaire" developed by Galton (1880, 1883) which required the subjects to recall, in the form of a visual image, the details of their breakfast table and to rate the clarity of the

image. The basic structure of Galton's approach was used in the development of The Questionnaire upon Mental Imagery (QMI) (Betts, 1909), which consisted of 150 items assessing the vividness of images taken from 7 different modalities, including the visual and kinaesthetic. A shortened version of the QMI was introduced by Sheehan (1967) who maintained the same format as the original and although widely used, the QMI has been criticised by Marks (1973) and Isaac, Marks and Russell (1986) because it lacks validity when applied to the assessment of performance based upon a specific modality.

Marks (1973) and Isaac *et al.* (1986) developed questionnaires that examine visual and movement imagery respectively. The Vividness of Movement Imagery Questionnaire (VMIQ) Isaac *et al.* (1986) was designed to investigate individual differences in visual imagery of movement and kinaesthetic imagery associated with particular movements. It consists of 24 statements instructing the subject to imagine making a specified movement, such as drawing a circle or jumping sideways. Each statement requires the subject first to imagine someone else performing the action and then to imagine themselves performing the same action. Subjects close their eyes, generate the appropriate image and then rate its vividness on a five-point scale from 1 - "perfectly clear and as vivid as normal vision" to 5 - "no image at all, you only 'know' that you are thinking of the skill".

The VMIQ was used to investigate imagery ability in a number of different groups including clumsy children, air traffic controllers and elite athletes from a wide variety of sporting domains (Isaac & Marks, 1994). Athletes reported their movement images to be significantly more vivid than matched controls, and ratings of vividness were highest in those who engaged in the performance of closed skills. Furthermore, imagery vividness of 'clumsy' children was significantly lower than that of age matched controls. Isaac and Marks (1994) suggest that this may reflect the importance of imagery in the development of the ability to plan movement.

The Movement Imagery Questionnaire (MIQ) (Hall, Pongrac and Buckolz, 1985) comprises 18 items which require subjects to perform an action and then rate the vividness of a visual and kinaesthetic image (on a 7 point scale) associated with the action. In a variation of this instrument, Hall and Pongrac (1983) used the same questions but instead of assessing the vividness of the images, this version of the MIQ assesses the ease with which subjects are able to generate an image.

Other self report questionnaires have addressed the question of whether subjects vary in their ability to control a visual image. The most widely used instrument of this kind is the Gordon Test of Visual Imagery Control (TVIC) Gordon (1949). The original consisted of 11 orally presented questions regarding the ability to manipulate visual images. Subjects responded either "yes" or " no". Subjects were classified as "controlled" or autonomous according to their performance. Slight modifications were made to the TVIC by Richardson (1969).

4.1.3 Performance Measures of Imagery Ability

Tests that fall into this category are assumed to rely on imagery processes and provide an observable response. Examples include mental rotation of 3D objects, e.g. Shepard and Metzler (1971), a variation of which was introduced by Vandenberg and Kuse (1978). The Mental Rotation Test (MRT) comprises of 20 items each of which consists of a target figure, two correct but rotated alternatives and two "distractor" figures which are either different in shape or are a mirror image of the target. To reduce the possibility of subjects using a guessing strategy each item is deemed correct only if both identical figures are identified.

Tasks used to investigate memory for movement and spatial information also fall into this category. Smyth and Scholey (1992) used a computer simulated version of the Corsi block task (De Renzi & Nichelli, 1975) in which subjects were presented with a 3 by 3

matrix of blocks, a series of 3 to 7 of which flashed according to a particular sequence. After a retention interval subjects had to recall the sequence by pointing to the blocks on a touch sensitive screen. Recall deteriorated if subjects made pointing movements to spatial targets during the retention period, demonstrating the spatial nature of the task. The linear positioning task used by Johnson (1982) is a further example of an objective task thought to involve imaginal processing. The results of this study also showed that spatial information interferes with the retention of a previously learned movement.

4.2 The relationship between subjective and objective measures.

Studies that have examined the relationship between self report questionnaires and objective tests of imagery ability have rather ambiguous findings. Some studies have shown that vividness is related to performance while others have failed to show any relationship. In a comparison of the effects of physical and mental practice (MP) on the improvement of swimming starts, White, Ashton and Lewis (1979) found that MP led to an improvement in performance. Improvement scores in the MP group exhibited a positive correlation with subjects' ratings of the vividness of kinaesthetic imagery taken from the QMI (Sheehan, 1967). Isaac *et al.* (1986), Marks (1977), Ryan and Simmons (1982) and Start and Richardson (1964) all provide additional evidence of the relationship between assessment of imagery vividness and the effects of MP. In the investigations of perceptual after-effects demonstrating the functional equivalence between real imagined and imagined movements, Finke (1979) reported that subjects classified as "good" imagers according to the VVIQ showed greater pointing after-effects following imagery than those subjects classified as "poor" imagers.

Other studies have examined the relationship between vividness and memory for movement. Good imagers (VVIQ) were consistently more accurate than poor imagers, in the recall of a previously learned end position (Housner and Hoffman, 1979). The reported vividness an image of the end location also exhibited a significant relationship

with accuracy of recall in the good imagers but not in the poor imagers. Further evidence of such a relationship was provided by Goss, Hall, Buckolz and Fishburne (1986) who demonstrated that high imagery ability (as assessed by the MIQ) was related to the acquisition of a sequence of movements but not to its retention in short term memory.

However, a large number of studies have failed to demonstrate any relationship between objective and subjective tasks. Walshe, Russell and Imanaka (1980) found no relationship between vividness as assessed by the MIQ and memory for distance and location information. Investigation of the relationship between vividness and other objective tests such as mental rotation have also failed consistently to find any significant relationship (Dean & Morris, 1991; Ernest, 1977; Poltrock & Brown, 1984). It is important to note that most of these studies used the Vividness of Visual Imagery Questionnaire (VVIQ) (Marks, 1973), which requires respondents to generate but not necessarily transform visual images. It is suggested that these two measures address static and dynamic imagery respectively, and may involve separate processes which could account for the consistent failure to observe any relationship. It is possible that a relationship would be observed if a questionnaire assessing the vividness of dynamic rather than static imagery was used in the analysis.

There is considerable controversy surrounding the reliability and validity of these self report questionnaires. Hall *et al.* (1985) report test-retest reliability of the MIQ over a one week period of r = 0.83, while Isaac *et al.* (1986) report a retest reliability the VMIQ of r = 0.76. Campos and Perez (1988) and Isaac (1990) (reported in Isaac & Marks, 1994) have also suggested that there is sufficient evidence to establish the reliability and validity of the VMIQ. Nonetheless, the validity of the MIQ has been called into question by Overby (1990) who failed to show any differences between vividness ratings between novice and experienced dancers.

Self report questionnaires do have some serious methodological difficulties. The demand characteristics of these questionnaires are very low and it is also likely subjects may assess characteristics of images according to different criteria. Indeed, Berger and Gaunitz (1979) and Ernest (1977) both reported that vividness scales are known to be affected by response bias, while Cohen and Saslona (1990) and McKelvie (1994) suggest that 'overconfidence' on the part of subjects may introduce considerable artifact into the data. Of equal importance is the fact that it is almost impossible to ensure that subjects comply with the experimental instructions.

Objective tests are assumed to free of such problems particularly with regard to compliance, but as Annett (1995) points out it is impossible to distinguish between compliance and ability when objective tests are used. In addition, these tasks are based on particular theoretical assumptions, e.g. the interference paradigm used by Baddeley and his colleagues is based on the assumption that certain tasks share a common processing component and that any cognitive system is subject to limitations of processing capacity. Thus, if one task selectively interferes with another then it implies that they share at least one component. Although, this paradigm has produced large amounts of data interpreted as highlighting the nature of imagery processes, it is still based on a rather indirect method and on the assumption of capacity limitations.

This is true of most theories of imagery, including Kosslyn's componential model. Individual differences in imagery ability was examined by assessing performance on a number of tasks thought to engage theoretical processes (Kosslyn, Brunn, Cave & Wallach, 1984). While providing evidence that imagery ability varies according to at least three important factors of imagery, this model is still hypothetical in terms of processes and structures. There is no *absolute* evidence that the processes set out in his model operate in the fashion described by Kosslyn; the evidence is still indirect.

The analysis of Kosslyn *et al.* (1984) was in relation to visual imagery and not to dynamic imagery *per se* and to date no similar approach has used to investigate these forms of imagery. This may be that dynamic imagery is still poorly understood, particularly with regard to the role of the motor system. However, the componential model of Kosslyn does have great heuristic value and the adoption of a similar approach in dynamic imagery may improve our understanding of its underlying components. The major difficulty would be to first identify the relative strength of modality specific representations in a given imagery scenario. One initial approach would be to use psychophysiological techniques to investigate individual differences in brain activity related to objective and subject measures thought to engage such representations.

4.3 Evidence from Psychophysiological Studies

In two EEG studies Marks, Uemura, Tatsuno and Imamura (1985) and Marks and Isaac (1995) reported significant differences in cortical activation (over the posterior regions) between subjects classified as good and poor imagers. In an ERP study that involved the generation of visual imagery, Farah *et al.* (1988) reported greater positivity at electrodes situated over the occipital lobes during the performance of an imagery task in a group of high imagers compared to a poor imagery group. Furthermore, Goldenberg *et al.* (1987) reported a positive correlation between the amount of rCBF in the inferior occipital cortex and the rating of the vividness of images. In these studies, subjects were grouped according to the score on the VVIQ which requires subjects to generate but not necessarily transform images. The nature of the items in the questionnaire was similar to the objective task used in the studies suggesting that subjective report may be related to performance.

Charlot *et al.* (1992) classified subjects according to their performance on two spatial tasks, the Minnesota Paper Form Board and the Mental Rotation Test (Vandenberg & Kuse, 1978). Measurement of brain activity during a visualisation task which had a large

spatial component showed that low imagers had an global increase in rCBF during the task whereas in good imagers increases in rCBF were localised particularly in the inferior parietal and occipital cortex. Charlot *et al.* argued that good imagers have a more 'differentiated cognitive architecture' resulting in more 'focal activation'.

Farah and Peronnet (1989) propose that the frequently reported failure to find a significant relationship between subjective report and mental rotation performance is a result of the different processes involved in these two measures. Thus, a significant relationship between imagery test scores and physiological measures should only be expected when the same underlying mechanisms are involved. This was shown in motor imagery tasks used by Marks and Isaac (1995). Good imagers classified according to the VMIQ showed an increase in alpha amplitude in the left posterior cortex of high imagers whereas low imagers showed a decrease in alpha amplitude. These results are important given the evidence of Beyer *et al.* (1990) who also found an increase in alpha during motor imagery. More importantly, these results show that individual differences in imagery are related to measures of psychophysiological activity.

4.4 Conclusion

In conclusion it is suggested that individual differences in imagery ability should be central to any investigation of dynamic imagery. The question that remains is what measures should be used to assess this important variable? As stated above, weaknesses exist in both subjective and objective instruments and there are disagreements as to their predictive value. One approach to this question is to use both kinds of instrument and examine their relationship to psychophysiological data recorded during objective and subjective tests of dynamic imagery. This would avoid potential problems related to bias in questionnaire data, thereby providing an additional objective instrument for the assessment of imagery ability.

Chapter 5

Methodology

In chapter 3 a review of the relevant literature demonstrated that there is considerable evidence supporting the contention that dynamic imagery involves many of the same neural structures known to be involved in perceptuo-motor behaviour. However, it was stated that all of the neuro-imaging techniques used in the relevant studies have their own strengths and weaknesses. The purpose of this chapter is first to discuss the merits of these techniques and second to describe the EEG technology used in the experiments reported in this thesis, the relevant methodology and the statistical procedures used to analyse the data.

5.1 Regional Cerebral Blood Flow Techniques

This method involves the administration of radioactive isotopes which attach themselves to blood molecules. Thus, when an area of the brain becomes active the amount of

radioactivity in that area changes accordingly. Fluctuations in the amount of radioactivity are detected enabling a detailed image of the brain to be taken. The temporal and spatial resolution of these techniques depend on the isotope used in the study. A number of the early PET studies reviewed in chapter 3 used the ^{133}Xe technique which involves the inhalation of labelled xenon gas. The major drawback of this technique is that it has poor spatial resolution and most studies are only able to take two dimensional pictures. This isotope also has a relatively long half-life so the task is performed for about five minutes for each PET image. This has important consequences as the image is hypothesised to reflect *only* the activity of interest, an assumption that cannot be ensured. Therefore, this method has poor spatial and temporal resolution.

More recent studies have either used an injection of 2-deoxy-D-glucose labelled with F-18 (FDG) or ^{15}O labelled water. The former technique is used to assess cerebral metabolism and has very poor temporal resolution having a 30 to 40 minutes uptake period. The use of ^{15}O is used in most contemporary PET studies of cognition having a half-life of only 2 minutes and spatial resolution of about 4-7 mm. It allows many scans to be taken in any one session, it being possible to take an image every 40 seconds. Although a great improvement on earlier techniques, this is still a very long time when one is trying to record cognitive activity that takes only milliseconds.

SPECT produces a 3D image but due to the isotopes used in this technique it has very poor spatial and temporal resolution. A further weakness is that large doses of the isotope are required to produce a good signal-to-noise ratio, so only one image can be taken during an experimental session.

Although these rCBF techniques have superior spatial resolution compared to EEG, they have other weaknesses which must be considered when assessing the significance of any data reported in these studies. First, these techniques are dependent on the subtraction method which involves the subtraction of an image considered to reflect a state of rest or

comparative inactivity, from the image which is taken during the experimental task. The underlying assumption of this method is that both images differ only with respect to the cognitive activity of interest. It is suggested hat one can never be certain that this assumption is upheld.

A further weakness is that there is great variation in the size and morphology of individual subject's brains. Thus before a group image is constructed, individual images have to be smoothed to fit a standard stereotaxic atlas. This results in the loss of crucial information as does the use of group images as they take no account of inter-subject variation in blood flow. These studies also only use very basic statistical procedures; in a typical PET study, t-tests are performed on individual pixels of two images reflecting activity of an experimental and control group respectively. One must, therefore, be very cautious when interpreting these data in isolation of other neuro-imaging techniques.

5.2 Functional Magnetic Resonance Imaging

FMRI superimposes rCBF image onto a structural image. This techniques has superb spatial (about 4mm) and temporal resolution (multiple images are taken every second). This method also has limitations, one major problem being the classification of artifact in the image; because the paramagnetic agent producing the signal is related to deoxygenated haemoglobin, an increase in the signal is found where large venous drainage systems occur in the brain. To date, no reliable method has been developed to overcome this problem and so the classification of artifact is left to the experimenter.

5.3 Electrophysiological Techniques

5.3.1 Electroencephalography

Electroencephalography (EEG) involves recording electrical potentials at the scalp thought to reflect the activity of neuronal ensembles located in the in cortex. This technique was used in all 5 experiments reported in this thesis and so will be described in much greater detail in section 5.4. At this stage, however, the reader should be made aware of the strengths and limitations of the EEG. The main benefit of this technique is that it is non-invasive and more adaptable than other techniques. It was primarily for these reasons and the nature of the experimental paradigms that the EEG was used in this thesis.

The EEG has major limitations. It has relatively poor temporal resolution - one to 5 seconds. It also has very poor spatial resolution due to the distance between the electrodes in an array; most studies use to 32 electrodes which means that the resolution is in centimetres compared to the millimetres resolution of blood flow techniques. This is further compounded by the fact that the electrical signal passes through the extra-cellular fluid and skull before it is detected by the electrodes. This smears the signal reducing the spatial resolution of an image and creates difficulties when trying to localise the source of the electrical signal.

5.3.2 Event Related Potentials

The ERP technique examines electrical activity of the cortex in the time domain. In a typical experiment brain activity is time-locked to a frequently presented stimulus and averaged over the number of presentations so that it appears as a potential superimposed on the naturally occurring 'noise' in the EEG. Compared to the frequency domain, ERPs provide more detailed temporal information of the underlying processes involved in a

task. Indeed it offers the best temporal resolution of all imaging techniques. individual components being detected between 70 and 700 ms. The main limitation of this task is that it necessitates the multiple presentation of stimuli, so the researcher must have a very clearly defined model in order to interpret ERPs. A further limitations of the approach is that it is subject to the same problem of poor spatial resolution as EEG.

In summary, it is evident that all contemporary neuro-imaging techniques have their relevant strengths and weaknesses, whether it be in relation to temporal and spatial resolution or to the restrictions imposed by the experimental environment. It is argued, however, that converging evidence from each of these techniques provides very important information about the localisation of cognitive representations. Given the hypothesis that dynamic imagery, particularly with regard to movement imagery, allows conscious examination of internal events over a period of time lasting more then milliseconds, then the EEG rather than the ERP was the adopted procedure.

5.4 Apparatus and EEG recording techniques used in this thesis

Two different EEG mapping systems were used for the five experiments presented in this thesis. Experiments 1 & 2 were conducted at the Department of Psychology, the University of Warwick and the EEG data were collected on-line using a 32 channel Neuroscience Series 3 Brain Mapping system. Experiments 3, 4 & 5 were conducted at the Defence Research Agency (DRA) Centre for Human Sciences, Farnborough, UK and the EEG data were collected using a 24 channel Nicolet SM2000 amplifier and BEAM II brain mapping system. Both systems record activity from surface electrodes arranged according to the International 10-20 System (Jasper, 1958). Any additional electrodes (as in the case in experiments 1 and 2) are located halfway between the standard sites and are named in a manner consistent with the 10-20 system.

5.4.1 The reference electrode

Although there have been recent developments in EEG recording including average-reference (e.g. common average reference) and reference-free recording techniques (e.g. the laplacian operator, Hjorth, 1980), the most common inactive reference sites are the earlobes and mastoids. Some researchers occasionally use a unilateral earlobe or mastoid as the reference but the majority employ the procedure of electrically linking electrodes on both earlobes (linked ears, A1 - A2) or mastoids (linked mastoids, M1 - M2). One methodological problem with this approach is that it is difficult to equalise the impedance of both electrodes; unequal impedance causes the amplitude of active electrodes on the side of the electrode with higher resistance to be artificially inflated (Garneski and Steelman, 1958). Katznelson (1981) has criticised this procedure on theoretical grounds; he arguing that it produces an artificial reduction in the difference between both hemispheres. He suggests that linking the ears or mastoids might provide a low resistive shunt across the head, thereby passing current from one hemisphere to another causing a reduction in any observable asymmetry.

Such a view has been supported by findings of Van Petten and Kutas (1988) who reported that a linked ears reference attenuated ERP asymmetry related to a linguistic task. Growing evidence suggests, however, that if the impedance of each electrode is similar then this problem does not arise (Andino, Marqui, Sosa, Lirio, Machado, Diaz, Rodriguez & Torrez, 1990; Lutzenberg & Elbert, 1991; Senulis & Davidson, 1989). There is no ideal solution for these problems and no consensus exists as to the best electrode reference to use. Linked ears is the most commonly used reference and was used in each of the five experiments, the researcher being aware of the issues surrounding its use.

5.4.2 Filtering and Digitisation

Filtering allows that portion of the frequency spectrum that is not of interest to be excluded from the recording. The very low and very high frequencies are filtered out by high and low pass filters, respectively. A further "notch" filter is used to exclude any mains supply that may leak into the system; this is characterised by a very sharp roll off allowing a very narrow frequency band to be excluded from the recording. The frequency range is very important as it affects the sampling rate necessary for accurate representation of the analogue signal in a digital form. The theorem of Nyquist requires that the data sampling rate is at least twice the highest frequency present in the signal. A high sampling rate avoids the problem of aliasing, or the mimicking of low frequency components by higher frequencies and in practice it is common to sample at least 3 to 4 times higher than the highest frequency in the signal. In Experiments 1 & 2 the high and low pass filters were set at 0.3 Hz and 40 Hz respectively. In Experiments 3,4 & 5 these filters were set at 1 Hz and 100 Hz.

5.4.3 Artifact Removal

All EEG recordings contain artifact whether it be of biological origin or leakage of recording equipment related 'noise'. and should be removed preferably before digitisation. The main source of biological artifact is eye movement, ECG, skin potential and muscle activity. Muscle activity is the most problematic; filtering cannot exclude it from the signal as its frequency spectrum is very broad and EMG activity can be as low as 12 Hz. It is crucial, therefore, that detailed visual inspection of the raw signal is made to exclude any obvious contamination as automated artifact rejection algorithms while detecting most of the 'noise' also miss a considerable amount.

The EEG systems used in the experiments did not have automated artifact rejection procedures and so great care was taken to visually inspect the raw EEG trace for signs of contamination. In addition, EOG channels were used to confirm the presence of large eye movements in suspect records. It is virtually impossible to remove all eye movement-related artifact, so data were accepted for further analysis when eye movements were too small and the absolute power in the delta band too low for there to be any effect on the higher frequency bands selected for analysis.

5.4.4 EEG Analysis

Modern developments in computer technology have made possible the detailed spectral analysis of the EEG signal through the application of the Fast Fourier Transform (FFT). This decomposes an EEG signal into its constituent elements, the main components of which are described in section 5.4.6. Prior to FFT the data are subjected to windowing as the removal of artifact results in a non continuous record of the EEG; the extraction of corrupted data results in an abrupt onset and offset of an epoch introducing artifactual frequency characteristics into the signal. The equipment described in this thesis used a Hanning Window which allows the beginning and end values of the two epochs to be reduced to zero amplitude while the middle of the epoch remains at 100% of its original amplitude.

Frequency resolution of the FFT is equal to the reciprocal of the epoch length, the longer the epoch the greater resolution of the frequency content. The Neuroscience system (experiments 1 & 2) used an epoch length of 2.56 seconds and the Nicolet (experiments 3, 4 & 5) used an epoch length of 2 seconds.

5.4.5 Quantification of the EEG

The EEG in each band is quantified in terms of either relative power or absolute power. Relative power is the amount of activity in a given frequency band in relation to the other frequency bands in the spectrum. It is derived by dividing the activity within that band by the activity of the other frequency bands and is expressed as a percentage. As relative power is dependent on activity in other bands it should never be reported in isolation. Where there are circumstances (e.g. if the background EEG is too high or too low), then it can be used in combination with absolute power in an attempt to explain the functional significance of changes in absolute power, though great caution must be taken in any interpretation.

Absolute power is the amount of activity in a given frequency band. It is usually quantified according to the square of the amplitude within a given frequency band, i.e. μV^2 though it is becoming increasingly common to quantify the EEG in terms of power density (Tomarken, Davidson, Wheeler & Kinney, 1992). In this approach absolute power is divided by the number of frequency bins in a given band, i.e. $\mu V^2/Hz$. This depends of course on the resolution of individual equipment, some provide a power value for every 0.5Hz others every 1 Hz. All data and statistical analyses discussed in this thesis are in relation to absolute power.

There is great inter-individual variability in the EEG power, which may be a result of the variability in skull thickness (Leissner, Lindholm & Peterson, 1970). This often results in skewed data, requiring a transformation into a more normal distribution. A log or square root transformation is frequently applied to the data though, Davidson, Chapman, Chapman and Henriques (1990) reported better distributional characteristics following log transformation. Although there is high inter-subject variability, measures of absolute and relative power at anterior and posterior sites have shown high test-retest reliability

(Fein, Galin, Yingling, Johnstone & Nelson, 1984; Gasser, Bacher & Steinberg, 1985; Lynch, Paskewitz & Orne, 1974; Van Dis, Corner, Dapper, Hanewald & Kok, 1979). Where data were skewed a log transformation was applied.

5.4.6 Frequency Components of the EEG

The main focus of most EEG research has been on the five classical wavebands within the 0-30 Hz frequency range, though some investigators (e.g. Spydell & Sheer 1982) have examined activity in the gamma (36-44 Hz) frequency range. The main frequency bands used to characterise the EEG are presented in Table 5.1

Table 5.1 Different EEG frequencies and their amplitudes

	Frequency (Hz)	Amplitude (μV)
Delta	0.5 - 3.5	up to 100-200
Theta	4 - 7.5	< 30
Alpha	8 - 13	30 - 50
Beta 1	13.5 - 20	< 20
Beta 2	20 - 30	< 20
Gamma	30 - 50	< 10

The divisions of the EEG spectrum into these bands are approximate, an approach that is not being without its critics (e.g. Lorig and Schwartz, 1989). The general consensus of

opinion is, however, that they are able to accurately describe the EEG, each of the bands having its own set of characteristics and components.

Only alpha and beta frequency were examined as Ray and Cole (1985) have propose that alpha and beta 1 reflect the attentional demands of a task whereas beta 2 reflects the cognitive demands. As statistical analyses in this thesis are restricted to alpha and beta, it is important that the frequency characteristics as well as the neuronal and functional significance of these wavebands are understood.

5.4.6.1 Alpha

Alpha activity (8 - 13 Hz) was named by Berger (1929) and is characterised by high amplitude waveforms that usually appears in the EEG in bursts of several seconds (alpha spindles). It is seen in about 75% of awake individuals and increases when an individual closes his eyes and is associated with a state of relaxation. In contrast the amount of alpha decreases when that individual open his eyes or engages in mental activity; this phenomenon is called *alpha blocking* or *desynchronisation*.

There have been a number of alternative theories as to the source of alpha generators. Lopes da Silva and Storm van Leeuwen (1978) proposed that the neural source of alpha generates a dipole field that is oriented perpendicular to the surface of the cortex. In a comparison of the activity recorded from surface and intra-cortical electrodes implanted into the visual cortex of dogs they found a 180 phase relationship between alpha recorded at the surface and alpha recorded sub-cortically. They concluded that at least one of the alpha generators is located at the same level of the pyramidal cells of the visual cortex. Andersen and Andersson (1968) also suggested that alpha is generated by pyramidal cells and that their activity is synchronised by thalamic nuclei; excitatory and inhibitory

postsynaptic potentials are locked in phase by "post inhibitory rebound." This model proposed that excitatory thalamic pacemaker nuclei are turned off by inhibitory interneurons for the duration of the Inhibitory Post Synaptic Potential (IPSP). When the IPSP ends, excitation of the pacemaker neurons begins anew.

The role of thalamus in the entrainment of EEG synchronisation is widely accepted but Andersen and Andersson's account of how it is achieved has been proved to be incorrect. Such mechanisms depend on the interaction of excitatory and inhibitory loops rather than just inhibitory rebound (Thatcher & Purpura, 1973). It is important to realise that connections between the cortex and the thalamus are reciprocal and thalamic neurons do not always 'drive' the cortex making it likely that pacemaker units operate at both a cortical and thalamic level. It is suggested that top down mechanisms are able to alter the output of thalamic neurons which in turn alter the oscillatory activity found at a cortical level. Indeed Nunez (1981) has argued that most of the input to a particular cortical area comes via cortico-cortical connections which are more influential than the thalamus in setting temporal and spatial characteristics of the EEG. This is important when assessing the effects of cognitive activity in humans as the cortex is significantly more developed than in lower animals.

5.4.6.2 Beta

Beta activity is characterised by high frequency (13.5 - 30 Hz), low amplitude activity and is usually sub-divided according to the higher or lower frequency components. In this thesis reference is made to beta 1 (13.5 - 20 Hz) and beta 2 (20-30 Hz), the slower and faster band having been associated with the processing of attention and cognitive related activity (Ray & Cole, 1985). Beta activity has been found to be reduced by effort and through emotional, auditory and tactile stimulation (Lindsley & Wicke, 1974). As with

alpha there have been numerous interpretations regarding its functional significance, the most common being that it is related to cortical activation (Darrow, 1957).

5.4.6.3 The Functional Significance of Alpha and Beta

The traditional view of EEG analysis proposed that alpha is the dominant frequency during a state of relaxation and quiescence, reflecting the temporally synchronised activity of large ensembles of neurons. When an individual engages in mental activity alpha is blocked and *replaced* by the faster beta frequencies, reflecting the desynchronisation of these neuronal pools. Such a view stemmed from the reliance on the visual inspection of the EEG, it being relatively easy to detect the appearance and disappearance of alpha spindles. Alpha and beta were hypothesised to have an inverse relationship (Shagass, 1972) and so were interpreted as providing an index of mental activity.

This view has been shown to be an oversimplification. A decrease in beta was found when the subject engaged in problem solving tasks. Vogel, Broverman and Klaiber (1968) reported patterns of beta activation that were related to individual differences in task performance, task difficulty and hemispheric organisation. Individuals who were better at automatised tasks (e.g. object naming - also left hemisphere processing) provided more successful solutions to difficult mathematics problems (left hemisphere processing) than those who were better at spatial tasks (right hemisphere processing). Furthermore, this was characterised by lower levels of beta (greater activation) in the high performance group. This is not to say that beta does not always decrease. For example, Sokolov (1963) reported an increase in beta when the subject was presented with novel stimuli which decreased when the subject became habituated and Ray and Cole (1985) reported an increase in beta during the performance of cognitive tasks.

Synchronisation occurs in every band and the idea that alpha and beta represent synchronised and desynchronised activity respectively, is not supported by neurophysiological evidence (Thatcher & John, 1977). As mentioned above, spectral analysis has shown that amplitude within the beta range may also *decrease* during mental activity (Spydell & Sheer, 1982; Berfield, Ray & Newcombe, 1986) and that alpha and beta are positively related (Davidson, Chapman, Chapman & Henriques, 1990). It is possible that mental activity is not always accompanied by the desynchronisation of distinct cortical neuronal populations; on the contrary they may become synchronised and in phase, resulting in an *increase* in alpha or beta . Such a question is best answered by an examination of the phase and spectral coherence between these different neuronal populations, a procedure which is beyond the scope of this thesis. One of the drawbacks of frequency analysis is that data is averaged across time, so that desynchronisation might mask the contribution of other synchronisation mechanisms.

In conclusion it is suggested that in most cases an increase in cognitive activity produces a decrease in alpha and beta power, reflecting the summated activity of different neuronal ensembles. It is also possible that cognitive activity may also result in an increase in frequency power though this phenomenon would be specific to certain kinds of tasks.

5.5 Statistical Analysis

A similar approach to statistical analysis was adopted in all five experiments described in this thesis. Topographical maps of the average power in each subject group, in each condition were created using resident Imager software for alpha, beta 1 and beta 2. Both the Neuroscience and Nicolet BEAM systems require power values of all the electrodes to generate topographic maps. The hypotheses under consideration require direct attention being paid to specific electrodes particularly those situated over the pre-frontal and temporo-parieto-occipital areas.

There are a number of serious drawbacks in the use of topographic mapping, the most important being that they are imprecise in localising EEG activity (Kahn, Weiner, Brenner & Coppola, 1988). The reference has also been shown to be crucial in the integrity of these displays as activity near this electrode is artificially attenuated. The use of a linked ears reference results in the lowest amplitude being displayed near the ears and the highest amplitude near the vertex so that genuine foci of activity are shifted medially (MacGillivray & Sawyers, 1988). If right-left differences are displayed the opposite is observed and displays of activity are shifted too laterally (Coppola, 1990).

A further problem is that topographical maps generally have very poor spatial resolution. Displays from the Neuroscience and the Nicolet systems comprise data recorded from 28 and 20 electrodes respectively with approximately 4-5 cms between each site. As a result, approximately 99% of the pixels in a colour display are an interpolation (in this case 4 electrodes) of the real data points. There is also a tendency to examine these maps like those derived from Computerised Tomography (CT), Positron Emission Tomography (PET) and Magnetic Resonance Imaging (MRI) techniques which have far superior spatial resolution. It is important to note that these maps do not provide any additional information regarding the origins of the EEG signal.

For these reasons no reliance was placed on visual inspection of the maps or on the limited statistical facilities built into the Imager's software. Instead a number of macro programmes were utilised to calculate the mean power at each electrode in each frequency band, these data being downloaded to a statistics package (Systat 5.2.1). This procedure was applied to the data for all subjects in each conditions of all five experiments. It is important to note that in experiments 1 and 2 the EEG was quantified in terms of power (μV^2) whereas as in experiments 3, 4 and 5 it is expressed in terms of power density ($\mu V^2/Hz$). Data in alpha frequency data were found to be skewed in all five experiments and were log transformed prior to further analysis. The distributions of

the data in the beta frequencies in experiments 1 and 2 were not transformed, the distributions being approximately normal. This was not the case in experiments 3, 4 and 5 and so the data were log transformed.

5.5.1 Analysis of Individual Differences

Experiments 1 and 2 were conducted at the University of Warwick which has the advantage of providing a large population of subjects. This allowed a large sample of subjects to be screened on the basis of their imagery ability; 84 subjects completed the VMIQ and ten subjects at each end of the continuum were selected as good and poor imagers respectively.

The first stage of statistical analysis was to perform a MANOVA which included group, conditions and electrodes as variables. This was then followed by ANOVA and the appropriate post hoc tests. The assumption of MANOVA that there should be more subjects than variables is met in all experiments but overall power is low. The standard procedure of carrying out univariate analyses only after a significant MANOVA provides a very conservative view of the data but since trends consistent with the underlying theory are of interest, it was decided to present the results of those univariate analyses which indicate these trends even when the MANOVA result would not strictly justify this procedure. Statistical power is often low in EEG studies due to the low ratio of subjects to variables and it is conventional to rely on univariate analysis to test hypotheses about the data. This approach is adopted in all five experiments described in this thesis and it is made clear when particular results meet the strictest criteria and when they can only be regarded as indicating trends.

Experiments 3, 4 and 5 were conducted at the DRA, Farnborough where a much smaller pool of subjects was available to participate in the experiments. This made it difficult to select subjects on the basis of their imagery ability assessed by self report questionnaire

and then classify them as either good or poor imagers. An examination of the distributions of these individual differences variables showed approximately normal distributions in each case, thereby excluding the use of a factorial design. It was decided to treat such measures as continuous variables even though such an approach provides less detailed information about the contribution of individual differences in such an analysis.

In experiments 3 and 4, the first stage of statistical analysis was to perform a MANOVA with condition and electrodes as variables. This was then followed by ANOVA and the appropriate post hoc tests. To investigate the relationship between individual differences in imagery ability and task related changes in EEG, difference scores were calculated between all four conditions (resulting in six sets of difference scores). Each set of difference scores was then used as a dependent variable in a regression analysis; that is, the individual differences data were used as predictor variables. As the six sets of difference scores have only three degrees of freedom, it was necessary to perform a multivariate multiple regression using three sets of difference scores. Given that the main focus of interest of these experiments was in relation to mental imagery, three sets of scores derived by the subtraction of data recorded in the baseline and movement conditions from the imagery condition, were used in the analyses. Further analysis was performed only when there was a significant omnibus test: those difference scores which were significantly predicted by measures of individual differences were submitted to univariate multiple regression. This provided the direction of the relationship between the EEG difference scores and measures of individual differences. It also allowed the calculation of the semi-partial correlation coefficient , thereby providing an estimate of the variance accounted for by a particular predictor variable when all the other variables in the equation were held constant. Having established which sets of difference scores were predicted by the individual differences variables, correlational analyses were then performed between the predictor variable and each pair of variables from which the difference scores were derived.

A similar approach was adopted in experiment 5. On the basis of the results following MANOVA (electrode x condition) and ANOVAs it was deemed necessary only to perform univariate multiple regression analysis. This included measures of individual differences as predictor variables and the difference in power density between the imagery and baseline conditions as the dependent variables. Correlational analysis was then performed between the predictor variables and each pair of variables from which the difference scores were derived.

In summary due to the availability of subjects, the question of how individual differences in imagery ability is related to changes in cortical activity is addressed differently in these studies. Chapters 1 and 2 incorporated a factorial design, subjects being classified as good and poor imagers. However, in Chapters 3, 4 and 5 the distributions of subjective and objective measures of imagery ability did not allow the separation of subjects into different groups so these measures were treated as continuous variables. A series of regression and correlational analyses were used to this investigate this question.

Chapter 6

Does the imaginary transformation of objects in space involve the motor system?

Experiment 1

6.1 Introduction

Paivio asserts that "all mental transformations engage motor processes that derive originally from active manipulations of the referent object..." (Paivio, 1986, page 72). In line with this assertion, evidence presented in chapters 2 and 3 suggests that the motor system is of crucial importance in the planning and initiation of goal directed movements that would underlie such active manipulations (Jeannerod, 1994; Roland *et al.*, 1980). It was also suggested that the motor system is involved in calculating a feedforward model so that one is able to predict the effects of a given transformation on a previously stored representation (Kosslyn, 1994).

6.1.1 Cortical representations of imaginary transformation

The pre-frontal and supplementary motor areas are thought to be involved in the planning and temporal characteristics of a complex sequence of movements (Eccles, 1982; Frith *et al.* 1991; Roland *et al.*, 1980), and are also considered to play a similar role in imagined action (Decety *et al.*, 1994; Roland *et al.*, 1980). It is hypothesised that these areas maybe involved in the mental transformation of 3D objects and may also be responsible for the inhibition of efferent commands to the motor output system that occur during active manipulation.

Considerable evidence was also presented demonstrating that successful mental transformation of a given stimulus engages processes that are visuo-spatial in nature. Data from brain damaged patients (e.g. Ratcliff, 1979) and from psychophysiological studies of normal subjects (e.g. Rosler *et al.*, 1990) suggests that mental transformations involve high level association areas of the parietal cortex. It is suggested that this kind of task involves the interaction of highly distributed processes comprised of both motor and sensory representations. It is that EEG responses during a mental transformation should index the involvement of motor and sensory systems.

It is argued throughout this thesis that a decrease in frequency power is not *always* associated with an increase in neural activation but is dependent upon the nature and characteristics of a given task. Thus, Furst (1976) and Ornstein *et al.* (1980) reported a decrease in alpha power during mental rotation whereas Ray and Cole (1985) reported an increase in beta power. The tasks used by Furst (1976) and Ornstein *et al.* (1980) are more similar to that used in this study and so it was predicted that there would be a reduction in alpha, and beta power during a MRT task. This assumes that there is an inverse relationship between EEG and neural activation. With respect to beta, a reduction in power is again taken to index cortical activation. Given the hypothesis that mental rotation involves both high-level motor and visuo-spatial processes this reduction in alpha

and beta power was predicted to be maximal over the parietal and pre-frontal areas of the cortex.

6.1.2 Individual differences in imagery ability

As discussed in Chapter 4, there have been three main approaches to the assessment of individual differences in imagery ability. Two of the methods are subjective in that they use questionnaires to gauge either subjects' use of imagery or the vividness of an evoked image. A third, more objective, method involves the performance of a task assumed to involve imaginal processes. Although a significant number of studies have failed to demonstrate any significant relationship between subjective measures of vividness and objective tests such as mental rotation, it is argued that questionnaires used previous research was concerned with static rather than dynamic imagery. Therefore, any investigation of the relationship between objective and subjective measures of dynamic imagery should ensure, wherever possible, that they both involve similar representations.

The first experiment examined the relationship between vividness of movement imagery assessed by a self report questionnaire (VMIQ) and performance on a task of imaginary transformation, as both measures are assumed to involve dynamic imagery. The VMIQ (Isaac, Marks & Russell 1986) measures movement imagery by requiring the subject to generate images of a series of actions and has the interesting feature that each item admits of two modes, the 'internal' or first person perspective and the 'external' or third person perspective. The external perspective in particular is believed to involve primarily visual or visuo-spatial processes, though it is argued that it also involves motor processes. The Mental Rotation Test (Vandenberg & Kuse, 1978) is used frequently in studies that examine imaginary transformations and is thought to engage visuo-spatial and motor processes (Kosslyn, 1994).

Although both measures address dynamic imagery they may involve different cognitive representations; one measure is concerned primarily with movement imagery whereas the other is concerned with imaginary transformations. Thus, although both are assumed to involve motor processes it is possible that they engage different sensory representations and processes. An examination of the relationship between MRT performance and self report scores on the VMIQ would provide some insight into this question.

The possibility that these tasks engage different representations has important implications for EEG research. Previous studies have shown that when classified according to *subjective* measures, good and poor imagers have different patterns of cortical activation during visual imagery (Farah *et al.*, 1988; Marks *et al.*, 1985; Marks and Isaac, 1995) and during movement imagery (Marks and Isaac, 1995). Similarly, differences in the EEG have been found between subjects classified as good and poor imagers according to more *objective* measures (Charlot *et al.*, 1992). It is important to note that tasks used in these studies engaged similar representations to those utilised during the assessment of individual differences. As well as providing additional objective evidence of the validity of both objective and subjective measures of imagery ability, these psychophysiological data highlight the importance of using behavioural tasks and measures of imagery ability that engage similar representations.

Given the possibility that the VMIQ and MRT may engage different representations, it was decided in the first instance to compare cortical activity of subjects classified according to their self report score on the VMIQ and in the second, to compare activity of subjects classified on the basis of their MRT performance. This would allow a more systematic examination of how subjective and objective measures of imagery ability are related to EEG activity.

A number of predictions were tested:

1. There would be a reduction in alpha and beta power from a baseline measure to a condition involving imaginary transformation. This reduction in power would be observed particularly over parietal cortex but also over pre-frontal cortex, implicating the involvement of visuo-spatial and high level motor processes.

2. If subjective and objective instruments of imagery ability provide a valid assessment of individual differences, and are related to EEG activity, then there would be a difference in the EEG of subjects classified as good and poor imagers by either method.

3. If the VMIQ and the MRT measure the same processes, then there would be a significant relationship between VMIQ and MRT scores.

6.2 Method

Subjects

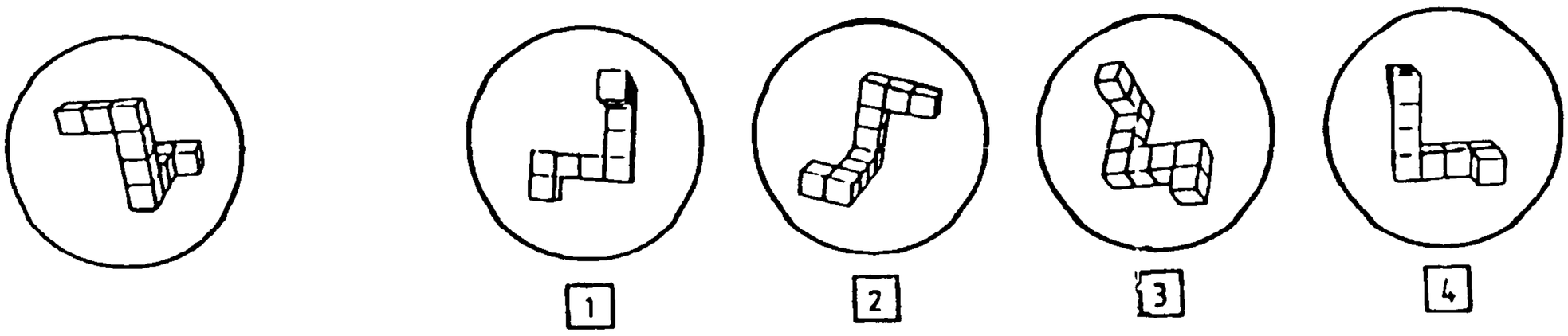
Subjects were initially chosen on the basis of their score on the Vividness of Movement Imagery Questionnaire (Isaac *et al.*, 1986). A sample of twenty right handed subjects (17 female, 3 male) aged 18-36 were selected from a population of 84 students at the Department of Psychology at the University of Warwick. Of the 84 subjects originally tested twenty whose scores on the VMIQ were at either end of the distribution were asked to participate in the experiment. The 10 subjects with the highest scores were classified as 'good' imagers and the 10 with the lowest scores were classified 'poor' imagers.

These same subjects were also classified as good and poor imagery groups according to their MRT performance recorded during the experiment. This was determined by median split, so two subjects whose scores fell exactly on the median value were omitted, there being nine remaining subjects in each group.

Apparatus and Materials

Twelve items were chosen from the Vandenberg and Kuse (1978) Mental Rotation Test. See Figure 6.1.

Figure 6.1 An item from the Vandenberg and Kuse Mental Rotation Test



Each item consists of a sample figure (on the left) and four test figures, two of which have to be matched to the sample. The test figures consist of two identical but rotated figures and two distractor figures which are either different in shape or mirror images of the sample. Each item was back projected onto a frosted glass screen using a manually controlled Kodak SA-V 2000 projector subtending a visual angle of 28 deg. 36 sec. from the sample figure on the left to the fourth comparison figure on the right. Subjects responded bimanually using two identical sets of four push-button keys in order to equalise changes in EEG due to motor responding. See Appendix C, Figure C6.1.

Apparatus and EEG Recording

The apparatus and details of EEG recording parameters are described in Chapter 5. Given the hypotheses under scrutiny five frontal electrodes (F3, Fz, F4, F7 and F8) and nine parietal electrodes (TCP1, TCP2, CP1, CP2, P3, PZ, P4, PO1 and PO2) were selected for statistical analysis.

Procedure

Baseline Condition

During the Eyes Open (EO) baseline condition subjects sat upright in front of the frosted screen. They were instructed to relax physically and mentally and keep as still as possible whilst fixating on a cross on the screen. They were also requested to keep eye blinks to a minimum and to keep the mouth slightly open to reduce jaw muscle artifact. Two minutes of EEG were then recorded.

Mental Rotation Condition

Subjects sat upright with their chin on a rest and were given three practice trials of the MRT to familiarise them with the test stimuli and response procedure. They were instructed to indicate which two of the four figures were identical to the target by pressing both spatially homologous keys simultaneously with both hands (see Appendix C, Figure C6.1). They were instructed to respond only when they knew which two figures were identical to the sample there being no time limit being placed on their judgements, i.e. accuracy rather than speed was emphasised. The presentation order of each test item was randomised across trials.

6.3 Results

In the mental rotation condition, to increase the likelihood that any recorded activity reflected the use of mental rotation, only epochs from trials in which the subject had *both figures correct* (60.41% of all trials) were chosen for analysis. The raw EEG trace for each epoch was visually inspected for artifact due to eye and other muscle movement. Approximately a further 20% of the data were rejected on account of eye movement related artifact. The 2.56 second epoch during which the subject made a manual response was also deleted to remove any effects of EMG activity. The mean duration of artifact

free data across all subjects was 27 epochs (68.1 seconds) for the eyes open baseline condition and 30 epochs (77.5) seconds for the mental rotation condition.

MANOVAs were conducted with group (good x poor imagers), condition (eyes open baseline x mental rotation) and site (the 14 electrodes specified above) as variables, followed by appropriate univariate analyses.

6.3.1 Location of mental rotation effects and correlates of subjective vividness

6.3.1.1 Behavioural Data

The mean and standard deviation of the VMIQ scores of both groups are presented in Table 6.1.

Table 6.1 Summary of means and standard deviations of the VMIQ in the good and poor imagery groups (VMIQ)

	Poor Imagery Group			Good Imagery Group		
	VMIQ_T	VMIQ_K	VMIQ_V	VMIQ_T	VMIQ_K	VMIQ_V
Mean	163.20	79.90	83.30	86.30	41.00	45.30
SD	31.64	19.15	16.12	15.87	9.67	8.23

T = Total Score
K = Kinaesthetic Imagery Score
V = Visual Imagery Score

Low scores on the VMIQ reflect vivid imagery and as the mid point of each of the sub-scales is 72, it is clear that the good imagers rate their images as being very vivid with a mean rating of between 1 and 2 for each item. In contrast the poor imagers produce a

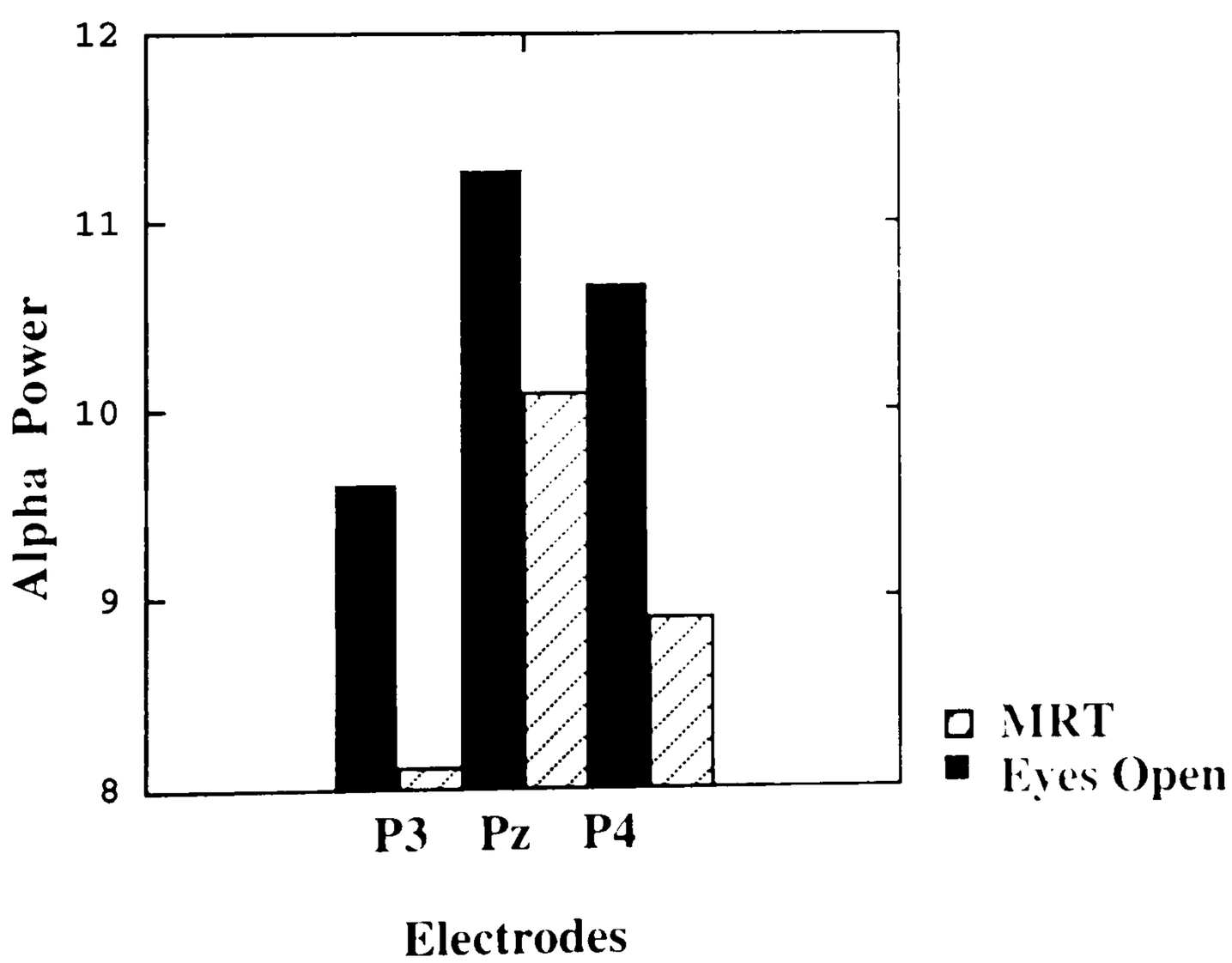
mean rating of between 3 and 4, indicating that they are not very clear or vivid. A t - test showed that the difference between the means of the two groups was highly significant. t (18) = 6.87, $p < 0.0005$.

6.3.1.2 Psychophysiological Data

Alpha

The means and standard deviations of EEG power values at each of the electrodes in the alpha frequency band during the two conditions are presented in Appendix A. Table A6.1. Alpha power decreased during the MRT condition at a number of sites, particularly those situated over the parietal lobes. See Figure 6.2.

Figure 6.2 Alpha power during MRT and Eyes Open Baseline conditions



As already noted above, the distributions in alpha were skewed and so it was necessary to transform the data; a comparison of a log and square root transformation showed that the former method resulted in less skew in the data (Davidson, Chapman, Chapman & Henriques, 1990). In line with this finding a log transformation was used on these data.

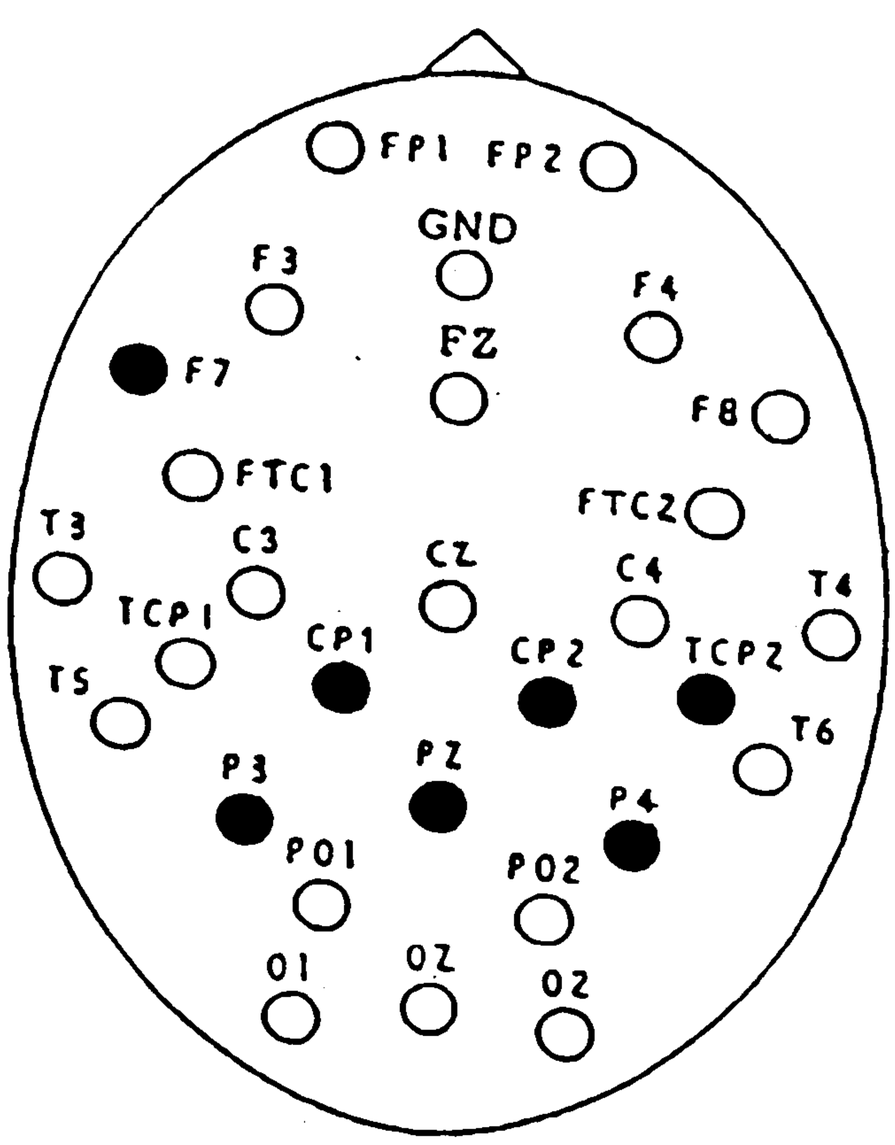
MANOVA indicated a significant condition effect [$F(14,5) = 11.148$, $p < 0.007$] but no group effect or interaction to indicate any effect of variation in subjective vividness. ANOVAs showed significant condition effects at a number of widely distributed sites. See Table 6.2.

Table 6.2 Electrodes at which main condition effects were observed in alpha

Electrode	d.f.	F-ratio	p
F7	1,18	6.384	0.021
CP1	1,18	7.869	0.012
CP2	1,18	8.802	0.008
TCP2	1,18	10.860	0.004
P3	1,18	6.615	0.019
Pz	1,18	7.485	0.014
P4	1,18	15.531	0.001

In each case alpha power was lower during MRT compared to the EO baseline. Those electrodes at which significant differences were observed are shown in Figure 6.3.

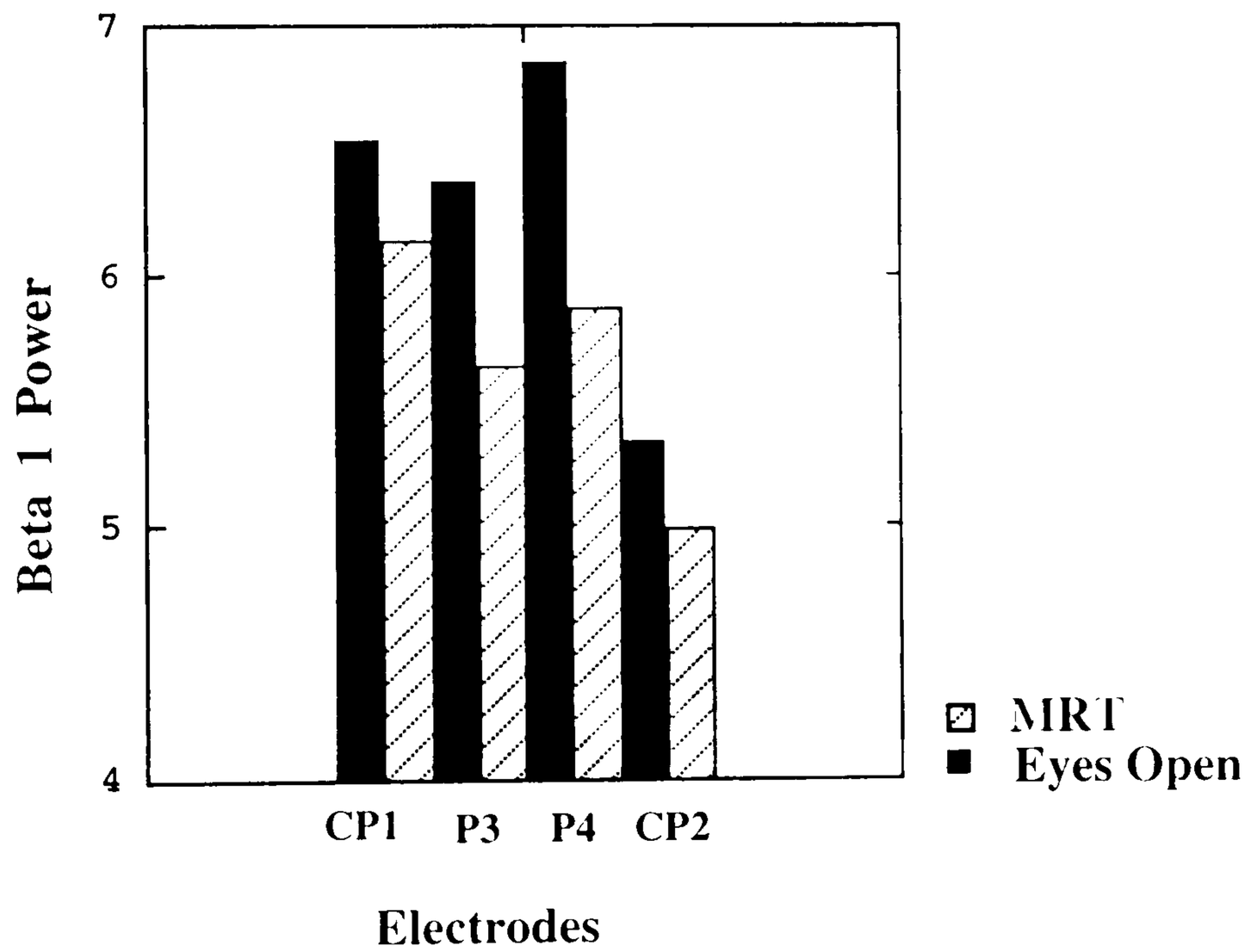
Figure 6.3 Figure showing locations of main conditions effects in alpha



Beta 1

The means and standard deviations of EEG power values at each of the electrodes in the beta 1 frequency band during EO and MRT are presented in Appendix A. Table A6.2. As expected, power values are lower in the beta 1 frequency and the data distributions are more symmetrical, lending support to the decision not to transform the data in this frequency band. Figure 6.4 shows a decrease in beta 1 power from the eyes open baseline to the MRT condition over central parietal regions.

Figure 6.4 Beta 1 power recorded during MRT and Eyes Open Baseline conditions



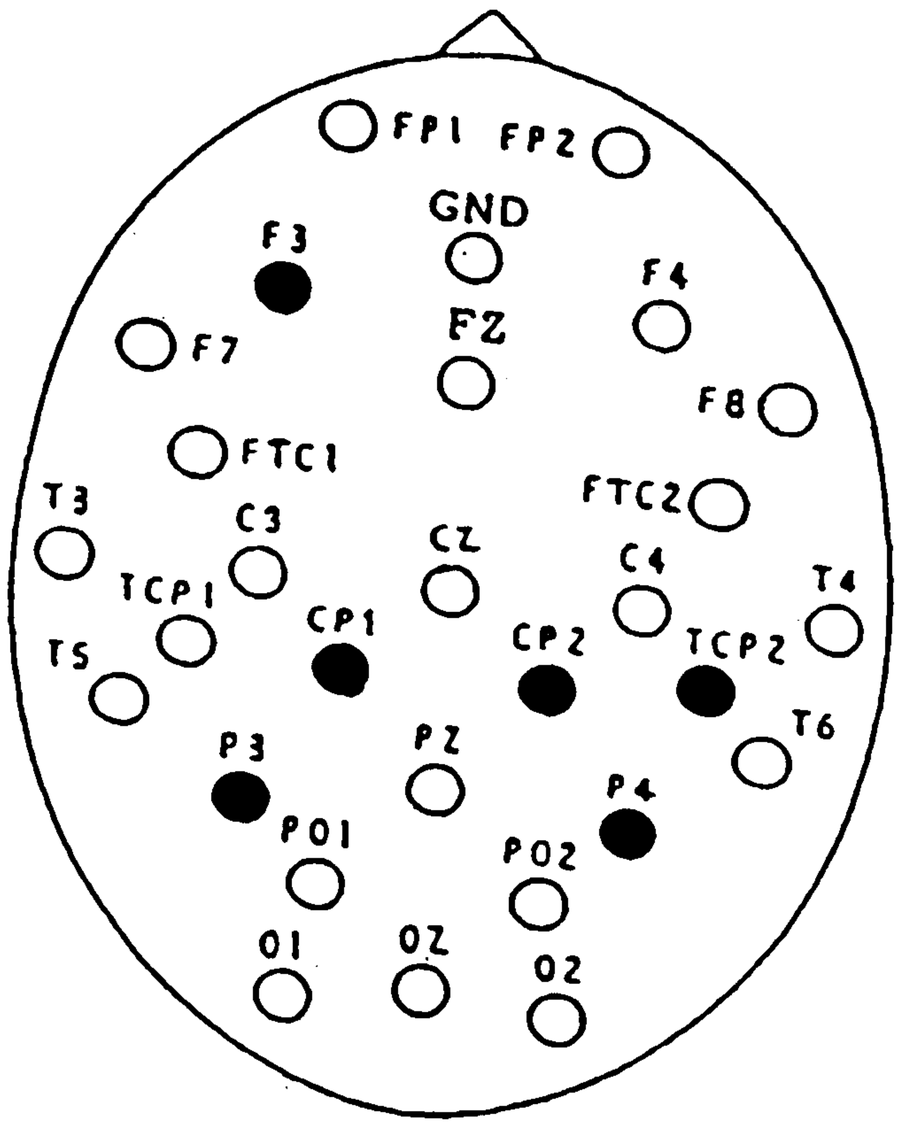
MANOVA indicated no significant main effects or interaction. However, trends in the condition effects were observed at many of the same electrodes found to be significant in alpha. (see Chapter 5 for a discussion of the reporting of statistics in this thesis). A summary of these trends are presented in Table 6.3.

Table 6.3 Electrodes at which main condition effects were observed in beta 1

Electrode	d.f	F-ratio	p
F3	1,18	6.685	0.019
CP1	1,18	4.711	0.040
CP2	1,18	4.897	0.040
TCP2	1,18	4.522	0.048
P3	1,18	4.492	0.048
P4	1,18	5.528	0.030

In each case power was lower during mental rotation (MRT) than during the eyes open baseline. Those electrodes which show significant differences are shown in Figure 6.5.

Figure 6.5 Figure showing locations of main conditions effects in beta 1

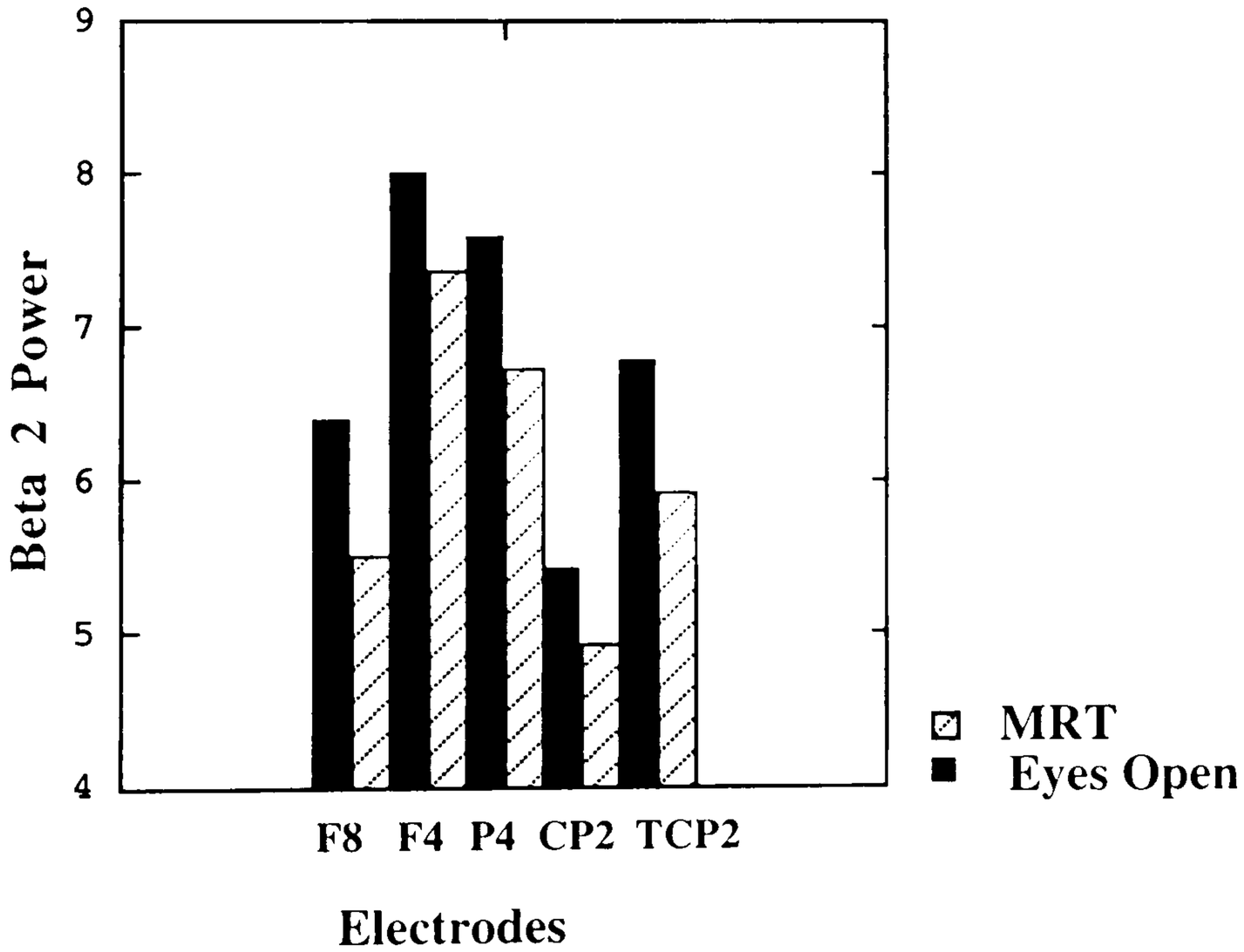


Beta 2

The means and standard deviations of EEG power values at each of the electrodes in the beta 2 frequency band during the two conditions are presented in Appendix A, Table A6.3. As in beta 1 there is lower variation compared to alpha but the most suprising

feature of the means in beta 2 is that they are higher than those observed in beta 1. Faster frequency components usually have lower amplitude. It is possible that these higher values reflect muscle related activity but this is unlikely as great care was taken to remove any muscle related artifact from the record. Furthermore, the means are also higher in the baseline condition where subjects were sitting in a state of relative quiescence. Though offering no clear explanation of this surprise finding, it could be that the description of a negative relationship between frequency and amplitude is an oversimplified generalisation. Figure 6.6 shows the decrease in power during MRT at electrodes situated over the right hemisphere

Figure 6.6 Beta 2 power recorded during MRT and Eyes Open Baseline conditions



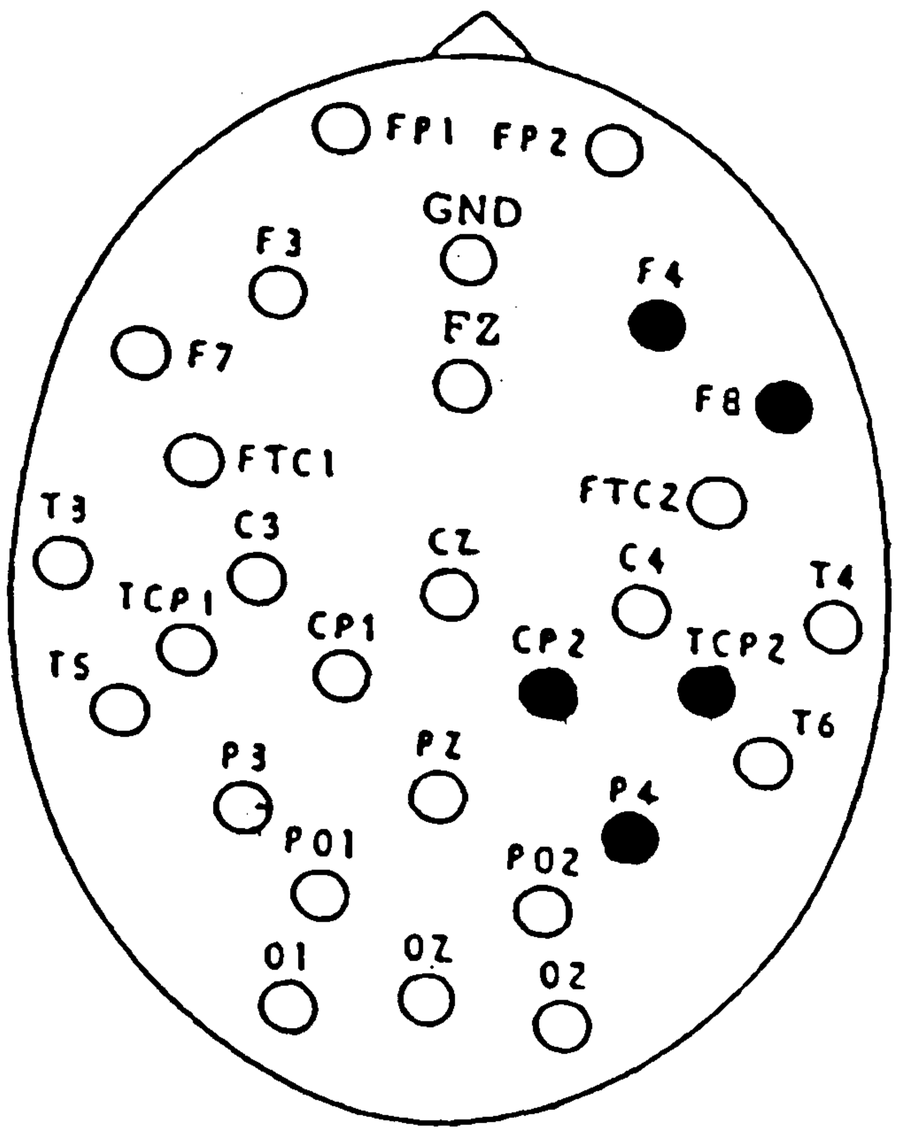
MANOVA indicated no significant main effects or interaction. Trends in condition effects were observed at electrodes over the right hemisphere. See Table 6.4

Table 6.4 Electrodes at which main condition effects were observed in beta 2

Electrode	d.f	F-ratio	p
F4	1,18	4.929	0.039
F8	1,18	6.756	0.018
CP2	1,18	5.766	0.027
TCP2	1,18	4.871	0.041
P4	1,18	5.793	0.027

The direction of the differences was identical to that observed in alpha and beta 1. Those electrodes which show significant differences are shown in Figure 6.7. There were no interactions or main group effects.

Figure 6.7 Figure showing locations of main conditions effects in beta 2



6.3.2 Location of rotation effects and correlates of MRT performance

6.3.2.1 Behavioural Data

The means and standard deviation of the scores of the good and poor MRT groups were 4.22 (2.10) and 10.22 (0.67) respectively. A two tailed t-test showed a significant difference between the groups [t (16) = 8.14 $p < 0.0005$]. The good imagers with an error rate on the MRT of only 15.75% were performing well above chance. The poor imagers had a much higher error rate of 64.81% but still performed better than chance.

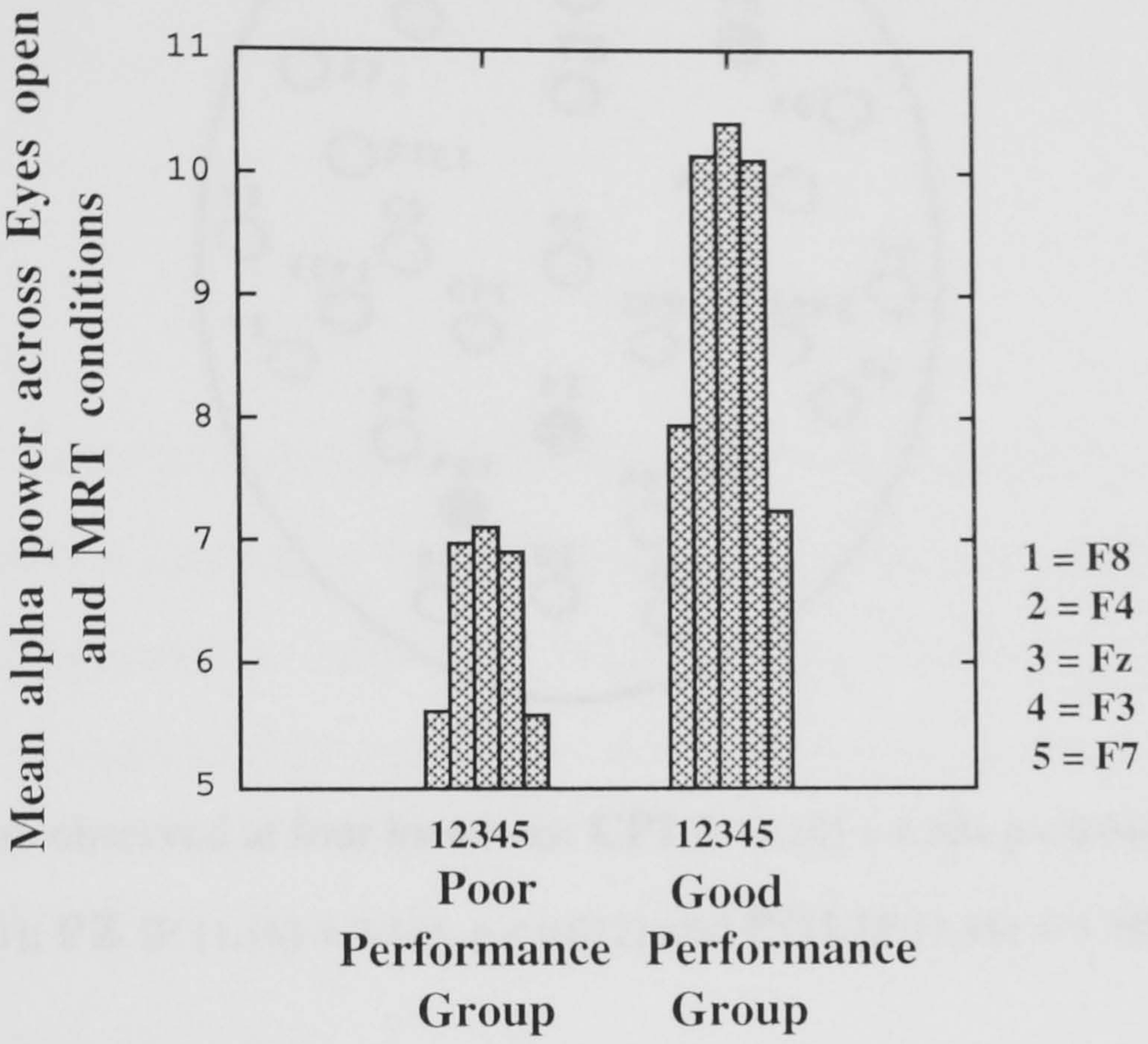
Pearson correlations between MRT performance and the VMIQ scales were found to be non-significant [total imagery score ($r = -0.177$, $p > 0.05$), visual imagery score (- 0.08, $p > 0.05$) and kinaesthetic imagery score (- 0.25, $p > 0.05$)]. An examination of the mental rotation performance data also failed to find any difference between the groups classified by subjective imagery vividness on the VMIQ, [t (18) = -0.68, $p > 0.51$]. The means and standard deviation of the scores for the poor and good VMIQ imagers were 6.80 (3.29) and 7.80 (3.33) respectively.

6.3.2.2 Psychophysiological Data

Alpha

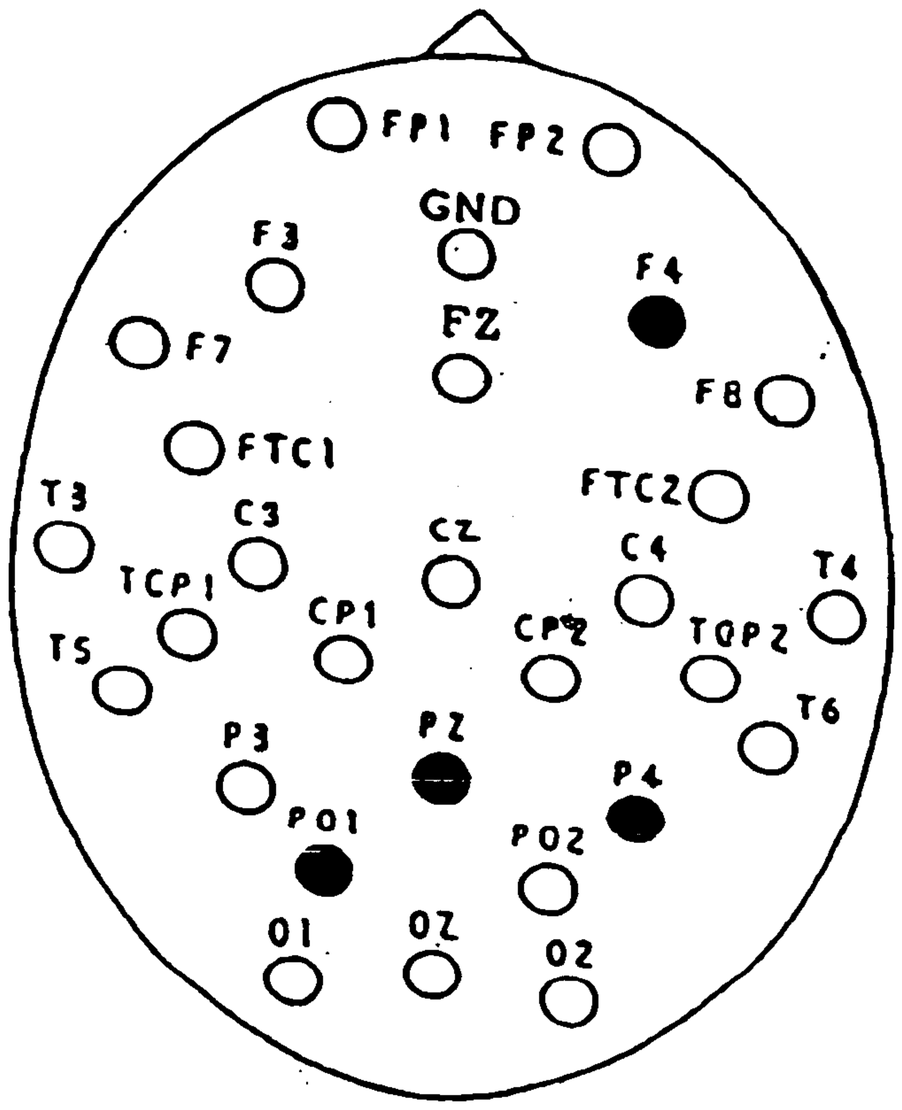
The means and standard deviations of EEG power values at each of the electrodes in the alpha frequency band during the two conditions in the good and poor *performance* groups are presented in Appendix A, Table A6.4. When subjects were classified according to MRT performance there are large differences in alpha power between good and poor imagers. There is also a corresponding increase in variation in the good performance group. The difference in power between the two groups is shown in Figure 6.8

Figure 6.8 Mean alpha power of high and poor performance groups across MRT and Eyes Open Baseline conditions



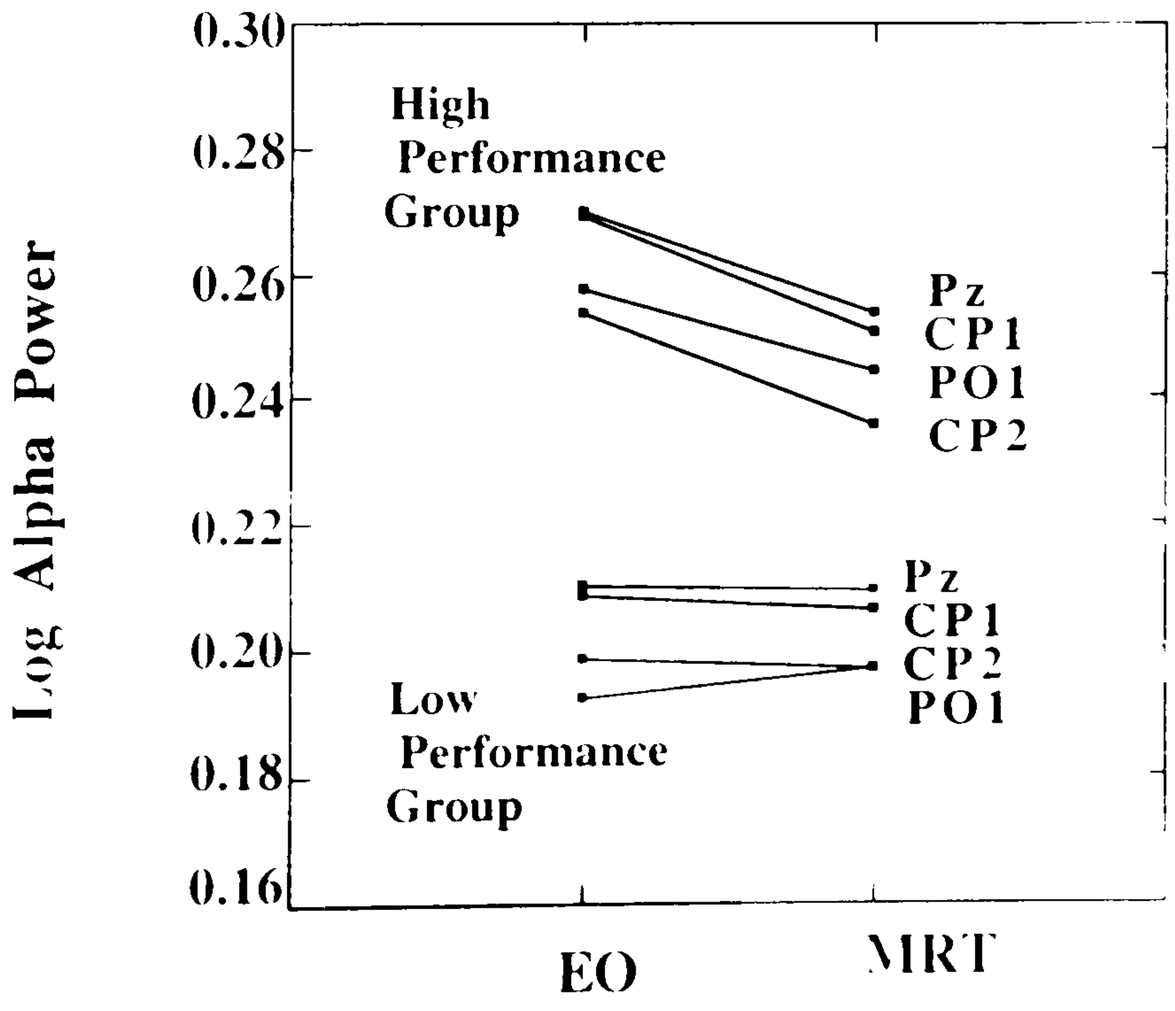
MANOVA showed a significant condition effect [$F(14,3) = 11.80$, $p < 0.033$], but no significant group effect or interaction. ANOVAs showed trends in group effects, the high performance group having a higher power at four locations: **F4** [$F\{1,16\} = 5.792$, $p < 0.029$]; **PZ** [$F\{1,16\} = 4.567$, $p < 0.048$]; **P4** [$F\{1,16\} = 5.919$, $p < 0.027$] and **PO1** [$F\{1,16\} = 8.917$, $p < 0.009$]. Those electrodes which show differences between good and poor imagers are shown in Figure 6.9.

Figure 6.9 Electrodes showing differences between good and poor MRT imagers



Interactions were observed at four locations: **CP1** [F {1,16} = 4.700, p < 0.046]; **CP2** [F {1,16} = 8.205, p < 0.011]; **PZ** [F {1,16} = 8.114, p < 0.012] and **PO1** [F {1,16} = 5.788, p < 0.029]. See Figure 6.10.

Figure 6.10 Difference in alpha power between eyes open (EO) and mental rotation (MRT) for good and poor performance groups



Higher levels of alpha were found in the high performance group during the baseline condition at **PZ** (Tukey $p < 0.022$), and **PO1** (Tukey $p < 0.033$). The trends in the high performance group indicated a decrease in alpha power from the EO to the MRT condition in central and parietal areas - **CP1** (Tukey $p < 0.002$), **CP2** (Tukey $p < 0.001$) and **PZ** (Tukey $p < 0.001$).

Beta 1

The means and standard deviations of EEG power values at each of the electrodes in the beta 1 frequency band during the two conditions in the good and poor MRT groups are presented in the Appendix A, Table A6.5. Power values in beta 1 are very similar in the two groups and indeed MANOVAs indicated no significant main effects or interaction.

Beta 2

The means and standard deviations of EEG power values at each of the electrodes in the beta 2 frequency band during EO and MRT in the good and poor MRT groups are presented in Appendix A, Table A6.6. As in the beta 1 frequency, there is very little difference between the levels of beta 2 power in the two groups. MANOVAs showed that there were no significant main effects or interaction.

6.4 Discussion

In experiment 1 a number of predictions were tested:

1. A reduction in alpha and beta power from a baseline measure to the MRT condition would be maximal over parietal regions due to their involvement in the processing of visuo-spatial information.

This first prediction was confirmed; during imagery, changes were found over parietal regions in all three frequency bands analysed, although according to the criteria laid down for the acceptance of univariate procedures, the results in beta 1 and beta 2 can only describe trends in the data. Even so, taken together with those in alpha, the results are interpreted as providing further evidence of the importance of the parietal cortex in the processing of visuo-spatial information during dynamic imagery.

It was also predicted that there would be a significant reduction in alpha power over the pre-frontal cortex, reflecting the involvement of high level motor processes. A decrease in alpha power was found over the left pre-frontal cortex (F7) and trends towards reduced power were also observed in beta 1 over the left pre-frontal region (F3) and in beta 2 over the right pre-frontal region (F4 and F8). These results are interpreted as highlighting the role of motor processes during imagery transformations.

2. A difference in the EEG of subjects classified as good and poor imagers both by the VMIQ and the MRT would be observed, demonstrating that both subjective and objective measures of dynamic imagery ability provide a valid assessment of imagery ability.

This prediction was partially support by the data; no relationship was observed between the *subjective* measure of imagery ability (VMIQ) and task related changes in EEG. A relationship was observed between an *objective* measure of imagery ability and task related changes in EEG; when subjects were classified according to their mental rotation performance, trends towards higher alpha in both baseline and imagery conditions were observed over both the frontal and parietal regions. There was also a trend towards a reduction in alpha during the MRT in the good imagers. The implication of this finding is that objective tests of imagery ability may provide a more valuable source of information regarding the relationship between individual differences and task related EEG activity.

3. It was expected that there would be significant relation between MRT and VMIQ scores demonstrating that they involve similar cognitive processes.

This prediction was not supported by the data. No relationship was found between the VMIQ score and MRT performance, a finding that is consistent with the psychophysiological data suggesting that the two measures engage different cognitive processes. Kosslyn (1994) describes movement imagery as involving " motion-encoded" processes (involving the activation of representations stored during perception) whereas transformation imagery involves "motion-added" processes which activation and transform a static image so that it 'moves' and alters the appearance of objects during encoding. Thus, although both instruments measure dynamic imagery, they apparently address different forms of dynamic imagery.

The results from the present study may be seen as providing additional evidence that the parietal regions are active during mental rotation tasks. They also indicate that the mental rotation task involves both hemispheres; bilateral changes in alpha and beta 1 implicate the involvement of both hemispheres though changes in beta 2 implicate the activity of the *right* hemisphere.

The exact role of each hemisphere is, however, controversial. Although there is a consensus that the right hemisphere has a central role in visuo-spatial processing, opinions as to the contribution of the left hemisphere are more varied. Fischer and Pellegrino (1988) suggest that the left hemisphere contributes to the non spatial elements of mental rotation, a view contrary to that held by De Renzi (1978). As noted above, Ray and Cole (1985) suggest that 8 to 20 Hz reflect the attentional demands of the task and the faster beta frequency bands reflect the cognitive demands but this could be an oversimplification. Bilateral changes in alpha and beta 1 over parietal areas during mental rotation would merely suggest that bilateral changes in alpha and beta 1 over parietal areas during mental rotation reflect attentional factors whereas changes in beta 2 over the

right hemisphere reflect cognitive processes such as image transformation. This would be consistent with the results of Ratcliff (1979).

Significant reductions in alpha associated with mental rotation were also found over pre-frontal regions. Over the left hemisphere there was a significant change in alpha and a similar trend in beta 1, whereas over the right hemisphere there was only a trend to reduced power in beta 2. The observed changes in the EEG over these areas could be interpreted as reflecting processes underlying the initiation of imagined movements and transformations. It is likely, however, that such changes do not reflect motor processes in isolation but also reflect their interaction with other putative frontal lobe functions including attentional processes and decision making.

Luria (1973) suggested frontal areas subserve "higher forms of attention", decision processes and the planning of motor commands. In the context of mental rotation these areas might be involved in a number of functions including the voluntary attention to a stimulus, the initiation of the rotation process, the identification of correct shapes subsequent to rotation (including the inhibition of competing distractor shapes) and the planning of the motor response. If Ray and Cole's (1985) interpretation of changes in the different frequency bands is correct, the implication from the current findings is that there may be an asymmetric functional organisation of these regions, the attentional and cognitive processes being lateralised to the left and right hemispheres respectively. It would also suggest that the observed changes in beta 2 reflect cognitive components of the task such as the comparison of the rotated image with an internal template of the target shape. This would be consistent with evidence demonstrating that the left anterior region is crucial for visuo-motor tasks involving mental rotation (Kim *et al.*, 1984) and indeed for the planning of motor control *per se* (Kimura, 1977). It is also consistent with the hypothesis that the right hemisphere has a central role in the transformation process itself (Deutsch *et al.*, 1988; Furst, 1976; Ratcliff, 1979).

With regard to the question of individual differences, there were no differences in the EEG good or poor VMIQ imagers which confirms previous research findings (Di Vesta *et al.*, 1971; Poltrock & Brown, 1984). Furthermore, no significant relationship was observed between subjects' mental rotation performance and their score on the VMIQ. This suggests either that different subprocesses were engaged (even though both tests measure dynamic imagery), or that subjective tests are not good measures of imagery ability. Given the evidence of Marks *et al.* (1985) and Marks and Isaac (1995) it is more likely that the absence of a relationship reflects the fact that the two measures involve different processes.

When subjects were categorised according to their rotation performance, trends *were* found in the EEG of high and low scoring groups. The group producing higher scores on the MRT was found to have higher levels of alpha, mainly over parietal areas, but also over the right pre-frontal region. Group effects describe the EEG activity across all conditions but the interaction show changes in the high performance group over parietal and central parietal areas during mental rotation similar to those reported by Charlot *et al.* (1992). Thus individuals with high levels of spatial ability may have more focal activation during spatial performance consistent with a more dedicated strategy involving the parietal areas.

6.5 Conclusion

The results of experiment 1 suggest that EEG measures may provide a useful index of variation in imagery ability. The observation that mental rotation involves both hemispheres but also contains elements that are more marked in the right hemisphere goes some way to explain the ambiguous findings of previous studies. Whilst this study did not examine the individual sub components of the MRT task, a design which allowed a more detailed examination of these components when using BEAM would be of obvious benefit.

The results do provide further evidence of the involvement of both motor and spatial systems in the mental transformations of 3D objects; the activation of the pre-frontal (particularly the left) cortex supports previous research demonstrating the involvement of high level motor areas in the imagery tasks (Decety *et al.*, 1994; Kim *et al.*, 1984). Given that parietal cortex is known to be involved in visuo-spatial processing, bilateral activation of this area during the MRT, together with changes over pre-frontal cortex, may be interpreted as demonstrating that imagery transformations involves widely distributed processes that involve both visuo-spatial and high level motoric representations.

Chapter 7

Does the imagination of bodily movement involve the motor system?

It was demonstrated in experiment 1 the pre-frontal and parietal areas of cortex were active during the imagined transformation of 3D objects. As discussed in Chapter 2, dynamic imagery also refers to imagery of movement or Mental Practice. It was suggested that different cortical representations are likely to be involved in movement imagery depending on the perspective adopted by the individual. Experiment 2 was an investigation of movement imagery and addresses three main questions: first whether high level motor processes are involved in movement imagery, second whether the perspective taken during imagery involves different sensory representations, resulting in different patterns of cortical activation, and third whether individual differences as measured by the VMIQ and MRT are related to the cortical activity recorded during the imagination of these action sequences.

Experiment 2

7.1 Introduction

As discussed in Chapter 2, differences between the 'internal' kinaesthetic and 'external' visual perspectives are recognised in the measurement of motor imagery (Isaac, Marks & Russell, 1986) and in the mental practice techniques recommended by sport psychologists (Hall, Rodgers & Barr, 1990). It has been argued that movement imagery taken from an internal perspective involves motor and sensory representations (Jeannerod, 1994), the latter being primarily kinaesthetic in nature (Epstein, 1980; Hale, 1982; Mahoney & Avener, 1977). In contrast, the adoption of an external perspective during movement imagery is said to engage representations that are visual or visuo-spatial in nature. It was argued that this interpretation is an over-simplification it being possible that imagery taken both from an internal perspective or external perspective may involve visuo-spatial and motor-kinaesthetic representations. The main focus of this chapter is to investigate those areas of the cortex that are active during the imagination of movement taken from both an internal and external perspective.

The adoption of an internal perspective is thought to engage representations involved in the planning and control of overt movements (Jeannerod, 1994). Roland *et al.* (1980) and Decety *et al.* (1994) using rCBF techniques demonstrated that the SMA and pre-frontal cortex are active during imagery of complex sequences of movement. The pre-frontal cortex has an important role in the attentional mechanisms related to controlling voluntary movement, including its planning and temporal organisation (Eccles, 1982). By the same token it is assumed to be involved in the planning and control of movement images (Jeannerod, 1994; Roland *et al.*, 1980).

It was suggested in Chapter 2 that this form of imagery may also involve visuo-spatial representations, particularly if an 'internal visual' perspective is taken. The parietal lobe

has been shown to be important in visually guided movement (Kalaska & Crammond, 1992; Taira *et al*, 1990). Given evidence of dense neural connections between parietal regions and motor regions of the frontal lobes (Fellerman & Van Essen, 1991) this suggests that representations located in the parieto-occipital region may become active during internal imagery.

The adoption of an external perspective is assumed to involve representations that are primarily visual or visuo-spatial. It has been argued that these representations maybe stored in high level visual association cortex and that during imagery, information is back propagated to the primary visual cortex where it activates retinotopically organised neural structures (Kosslyn, 1993). Activation of primary visual cortex during imagery has been interpreted as supporting the hypothesis that visual images maintain the structural characteristics of perception (Kosslyn, 1980). Therefore, external imagery should lead to a change in activity primarily over the parieto-occipital area of the cortex.

It was also suggested in Chapter 2 that this form of imagery may also have a motor component; di Pelligrino *et al.* (1992) reported that the visual encoding of movement information activates cells in the premotor cortex. Given the assumption that imagery activates representations stored during the encoding of movement information it is possible that a similar form of motor activity occurs during external imagery .

As discussed in Chapter 5, most researchers assume that a decrease in frequency reflects an increase in cortical activation. It was noted that changes in the EEG may not be as straightforward as this suggests; for example some researchers have observed an increase in power during movement imagery (Beyer *et al.*, 1990; Marks & Isaac, 1994), whereas others have observed a decrease in power (Breitling *et al.*, 1986). It is likely that the direction of changes in frequency power is related to the demand characteristics of a given task. Given the wealth of evidence that an increase in cortical activation is

characterised by a decrease in frequency power, it was hypothesised that the EEG would decrease during the imagery conditions compared to a baseline condition.

A number of predictions were made:

1. There would be a decrease in alpha and beta power from a baseline measure to a condition in which subjects imagine different movements taken from the VMIQ. This decrease in alpha and beta power would be dependent on the perspective taken during the imagery.

a) The adoption of an internal perspective would result in a decrease in power, primarily over pre-frontal cortex but also over parieto-occipital cortex.

b) The adoption of an external perspective would result in a decrease in power primarily over parieto-occipital cortex but also over pre-frontal cortex .

2. It was also expected that differences in the EEG of good and poor imagers, classified according to objective and subjective measures (VMIQ and MRT), would be observed during these different imagery conditions.

7.2 Method

Subjects

In experiment 2 EEG recordings were taken from the same 20 subjects who participated in experiment 1 whilst they imagined actions taken from a sub-set of items in the VMIQ, both from the internal and external perspective. This was done during the same recording session as experiment 1, half the subjects performing the VMIQ task before the mental rotation task and half doing the tasks in the alternate order.

Apparatus and Materials

The first 12 statements were taken from the VMIQ (see Appendix B). Each statement on the questionnaire takes a first person, or internal perspective ("imagine yourself...") and also a third person, or external, perspective ("imagine someone else..."). The resulting 24 statements were individually presented on slides, back-projected by a Kodak SA_V 1030 onto a frosted screen. The timing of the projector was controlled by a HyperCard programme running on a Macintosh IIci via a 'slave' system. EEG was recorded as described in chapter 5.

Procedure

Baseline Condition

Subjects sat upright with their eyes closed (the VMIQ requires subjects to imagine the movements with their eyes closed so it was necessary to have an equivalent baseline). As in experiment 1 they were instructed to relax, minimise eye movement and to keep the mouth slightly open. EEG was recorded for two minutes.

Movement Imagery Conditions

Each statement from the VMIQ was presented for three seconds and then removed. At this point subjects closed their eyes and were instructed to imagine the act referred to in the statement. A two second time lag was allowed after each instruction for subjects to close their eyes and begin to generate an image. EEG was then recorded for ten seconds. The subject was then asked to give a rating of the vividness of the evoked image. Twelve statements in one perspective were followed by twelve statements in the alternate perspective, the order of which was counterbalanced across subjects.

7.3 Results

7.3.1 Behavioural data

As a test of reliability, Pearson's correlations were performed between the vividness ratings of images evoked during the movement imagery conditions of this experiment and those reported during the pre-selection phase of the experiment. These tests were found to be significant: the first person perspective ($r = 0.779$, $p < 0.0005$), the third person perspective ($r = 0.759$, $p < 0.0005$) and the total score ($r = 0.709$, $p < 0.0005$).

7.3.2 Psychophysiological data

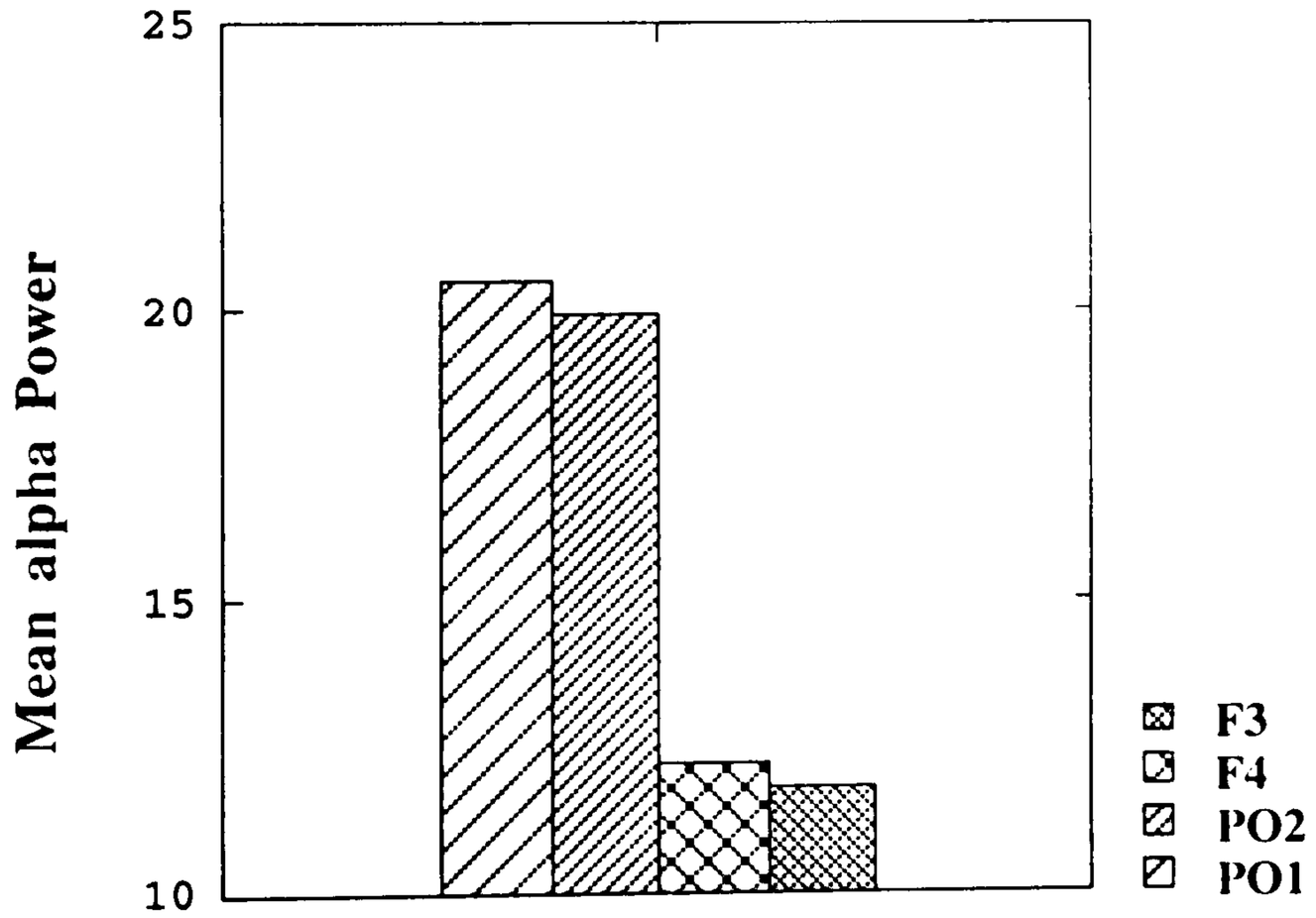
As a result of artifact rejection procedures described in chapter 5, 46 percent of the data were rejected. The data set comprised an average 27 artifact free epochs of EEG (approximately 69 seconds) across all subjects for the eyes closed baseline condition, 26 epochs for the internal perspective condition and 26 epochs for the external perspective condition. Electrodes were selected for analysis on the basis of their relevance to the hypotheses under test. Electrodes over the pre-frontal (F3, FZ, F4, F7 and F8). and posterior areas (T5, P3, PZ, P4, T6, PO1, PO2, O1, OZ and O2) were selected for analysis as they are over cortical areas thought to be involved the planning of movement and in the generation and inspection of visuo-spatial images. As in experiment 1 the data in alpha were found to be skewed and were log transformed. MANOVAs were conducted with group (good x poor imagers), condition (eyes closed baseline x internal perspective imagery x external perspective imagery) and site (the 15 electrodes specified above) as variables, followed by appropriate univariate analyses.

7.3.2.1 Location of imagery effects and correlates of subjective vividness

Alpha

The means and standard deviations of EEG power values at each of the electrodes in the alpha frequency band during the three conditions are presented in appendix A, Table A7.1. It is clear that levels of alpha are considerably higher than those observed in experiment 1. This is consistent with the common observation that alpha is greater when subjects' eyes are closed and becomes attenuated when they are opened. Figure 7.1 shows that there are higher levels of alpha at electrodes recorded over parieto-occipital areas compared to frontal regions, an observation that is consistent with the theory that alpha generators are located in posterior regions of the cortex.

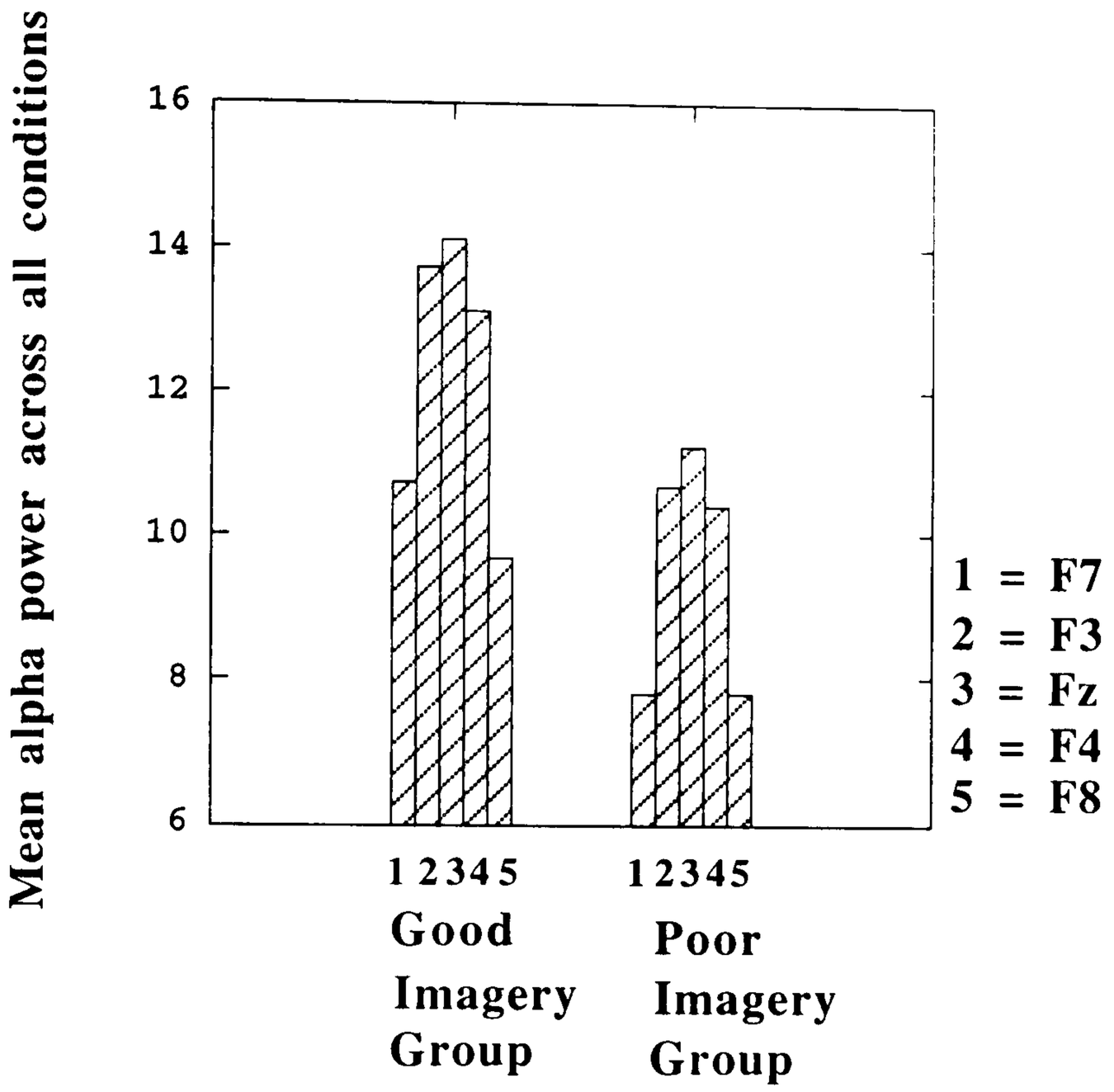
Figure 7.1 Mean alpha power during all three conditions at parieto-occipital and pre-frontal electrodes



Mean power values shown in Table A.7.1 suggest that there is greater alpha power in the good imagery group compared to the poor imagery group, a finding that is consistent

across all electrode sites. Figure 7.2 shows clearly the difference in power between the two groups over the frontal regions.

Figure 7.2 Mean alpha power in good and poor (VMIQ) imagers

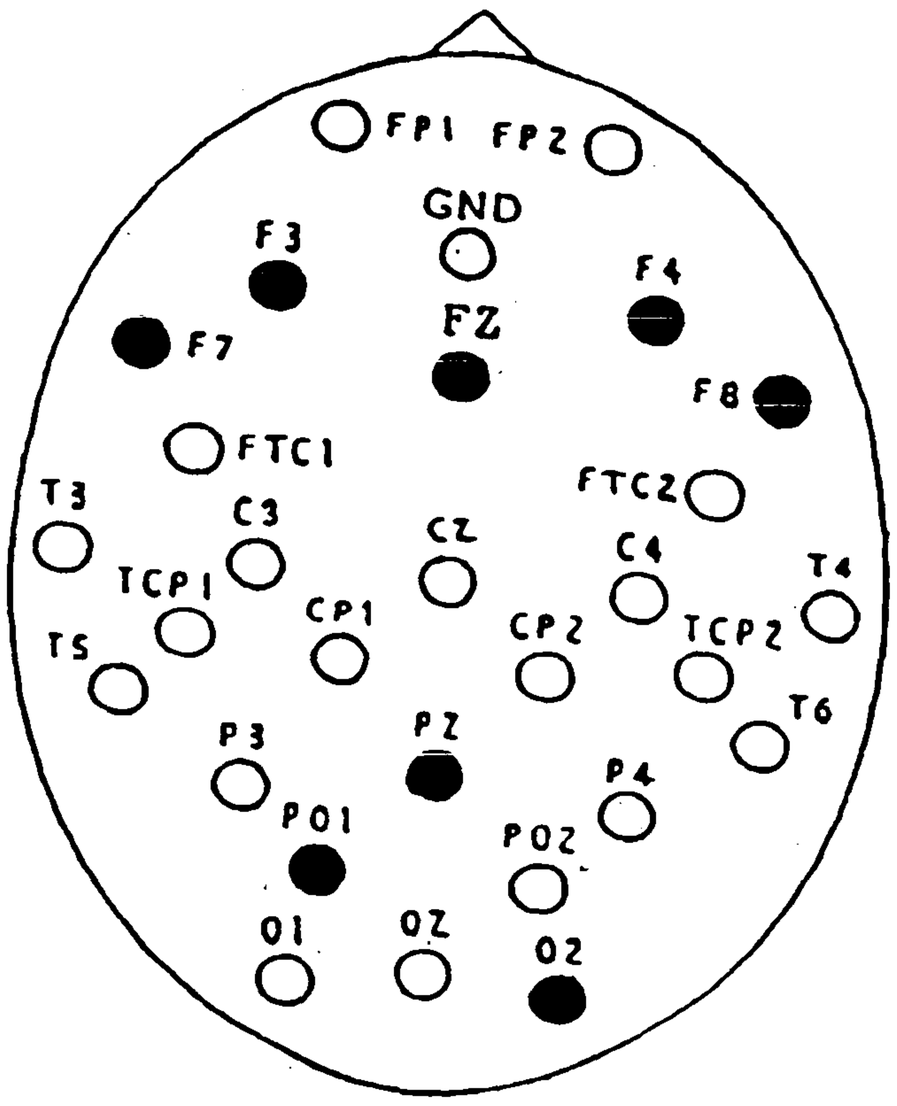


As in experiment 1 there is considerable variation in alpha levels particularly over posterior sites; as power increases so too does the variation. A common diagnostic check on data integrity is to examine the relationship between the mean and the standard deviation; a linear relationship implies that the size of the means being compared in an ANOVA are artifactually affected by variation in the different distributions. This is despite the fact that this phenomenon is consistently observed in data recorded in many different experimental settings (Chater, 1995). The data recorded from posterior sites provide a good example of this phenomenon; a comparison of alpha levels in the same subjects recorded during eyes open and eyes closed shows how variation increases in relation to the increase in the power. However, to satisfy the criteria of the statistical model being applied, the data were log transformed.

Table 7.1 Electrodes at which main condition effects were observed in alpha

Electrode	d.f.	F-ratio	p
F7	1, 18	7.152	0.015
F3	1, 18	5.123	0.034
Fz	1, 18	4.402	0.05
F4	1, 18	4.886	0.04
F8	1, 18	5.00	0.038
PO1	1, 18	6.846	0.017
Pz	1, 18	5.976	0.025
O2	1, 18	5.784	0.028

Figure 7.3 Electrodes showing differences in alpha between good and poor VMIQ imagers



MANOVA showed no significant main effects or interaction. As can be seen from Table 7.1, trends were found for group effects at all of the frontal electrodes and also at some posterior sites. In each case the high imagery group showed *higher* alpha power than the low imagery group. Those electrodes which indicate these trends are shown in Figure 7.3.

Beta 1

The means and standard deviations of EEG power values at each of the electrodes in the beta 1 frequency band during the three conditions are presented in Appendix A, Table A7.2. As in alpha, beta 1 power increases when subjects have their eyes closed. Such an observation suggests that there is a linear relationship between alpha and beta 1 and throws doubt on the suggestion that the faster beta components of the EEG signal increase in power when alpha is suppressed (Shagass, 1972). Alternatively this could be interpreted as showing that there is some degree of 'overlap' in the frequencies; the division of the EEG into different frequency bands is rather arbitrary so it is possible that the higher alpha and lower beta frequency components are related to the same kind of processing. A more likely suggestion is that alpha and beta increase and decrease in unison depending on the experimental conditions. Correlational analyses would provide some insight into this question but as only the alpha frequency has been log transformed this is not possible. Unlike data in alpha there appears to be very little difference between good and poor imagers or between the different conditions. Indeed no effects were observed using either multivariate and univariate procedures.

Beta 2

The means and standard deviations of EEG power values at each of the electrodes in the beta 2 frequency band during the three conditions are presented in Appendix A, Table A7.3. As in experiment 1 levels of beta 2 power were higher than beta 1. This could be as a result of undetected muscle activity but this seems unlikely given the artifact removal procedure. There are no apparent differences between the conditions or between good and poor imagers. However, MANOVA showed a significant group effect, [$F(15,4) = 12.299$, $P < 0.013$]. ANOVAs showed that the high imagery group had greater power at **F7** [$F(1,18) = 6.179$, $p < 0.023$].

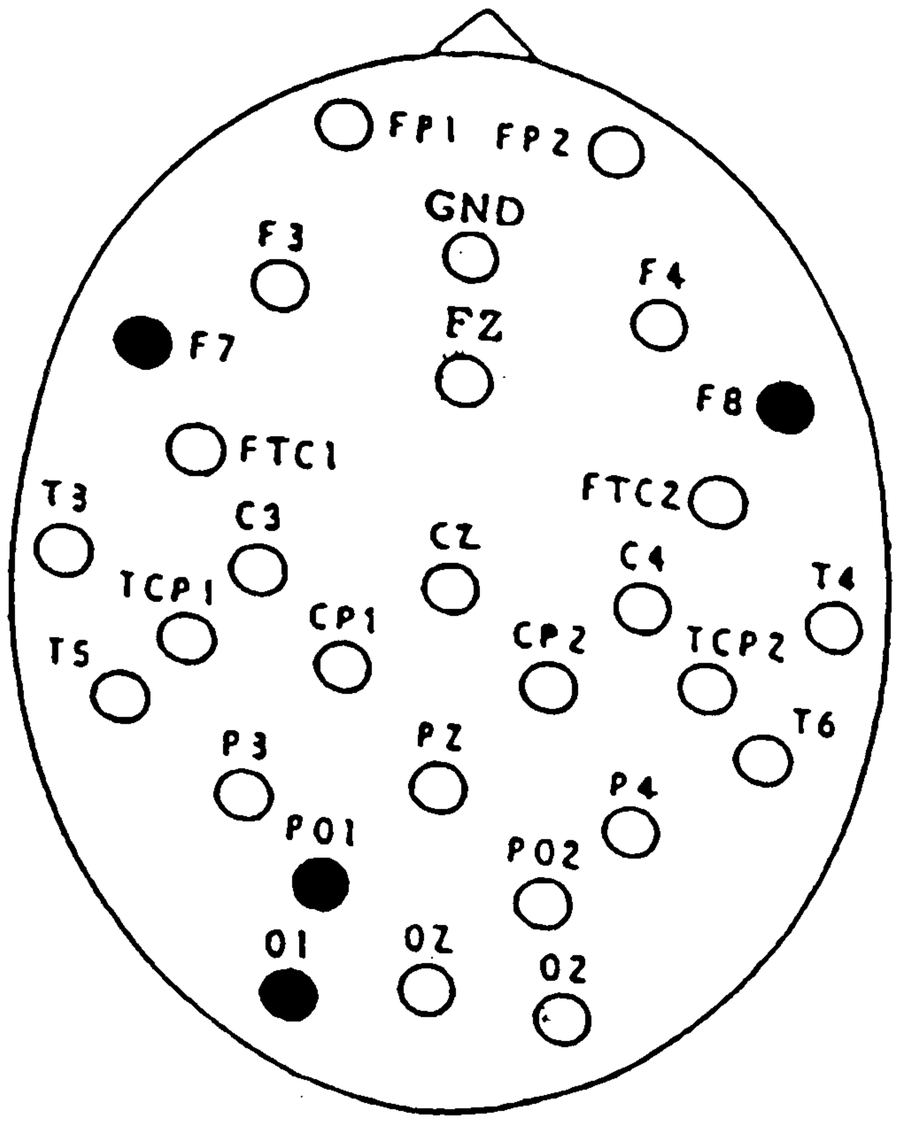
7.3.2.2 Location of rotation effects and correlates of MRT performance

In experiment 1 it was found that significant changes in EEG activity were related to an objective measure of imagery ability (MRT) but not to a subjective measure (VMIQ). In experiment 2 it was also observed that there were no differences between subjects classified as good or poor imagers based on the VMIQ so it was decided to once again re-classify subjects on the basis of the MRT performance.

Alpha

The means and standard deviations of EEG power values at each of the electrodes in the alpha frequency band during the three conditions are presented in Appendix A, Table A7.4. Subjects classified as good MRT imagers appear to have higher alpha power than poor imagers. MANOVA showed no significant main effects or interaction but ANOVA showed trends in group effects, the good MRT group having higher power at four locations: (**F7** [F {1,16}= 4.524, $p < 0.049$]; **F8** [{1,16} = 5.281, $p = 0.035$]; **PO1** [{1,16} = 5.088, $p = 0.038$]; and **O1** [{1,16} = 5.564, $p = 0.031$]). Those electrodes which show significant differences are shown in Figure 7.4.

Figure 7.4 Electrodes showing differences in alpha between good and poor MRT imagers



Beta 1

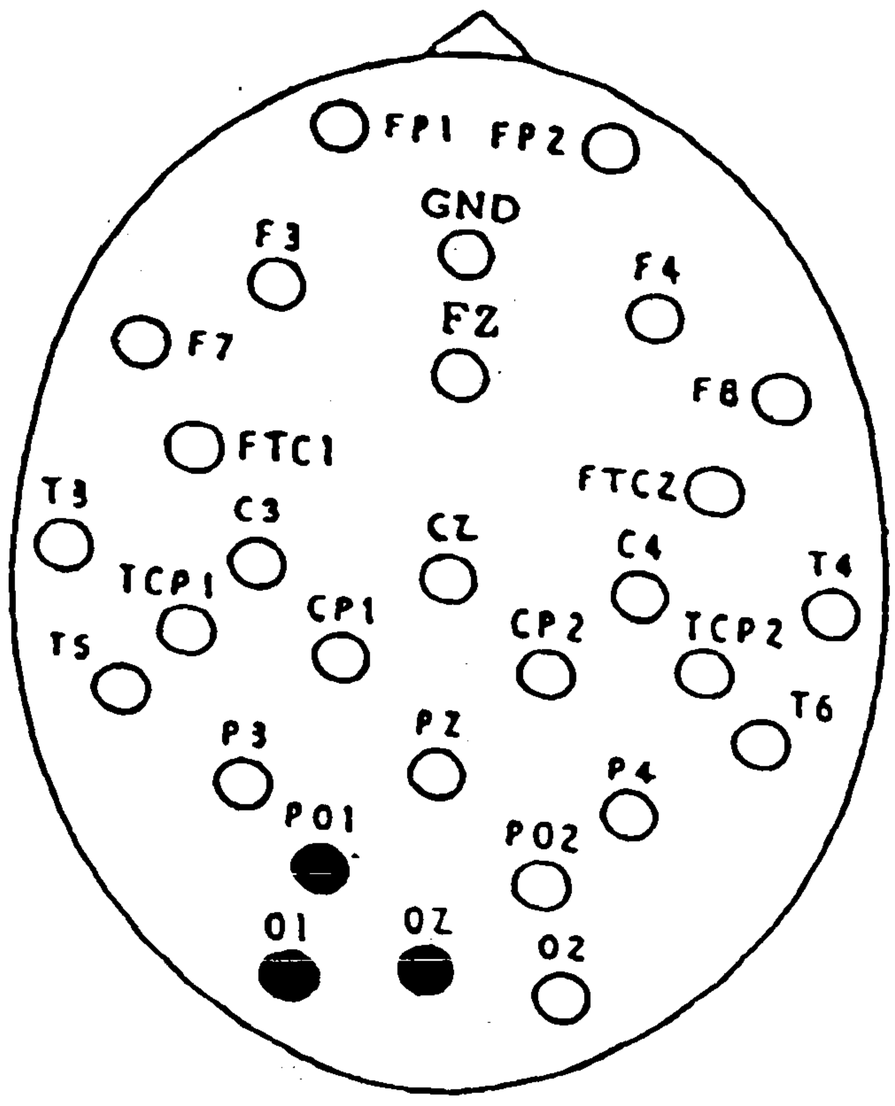
The means and standard deviations of EEG power values at each of the electrodes in the beta 1 frequency band during the three conditions are presented in Appendix A, Table A7.5. There appears to be very little difference between the two groups or between the three conditions. This was borne out by MANOVAS which showed no main effects or interaction. ANOVAS showed that good MRT performers had higher beta 1 at **O1**, $F(1,16) = 6.434$, $p = 0.022$.

Beta 2

The means and standard deviations of EEG power values at each of the electrodes in the beta 2 frequency band during the three conditions are presented in Appendix A, Table A7.6. MANOVA showed no significant main effects or interaction. Trends were found

for group effects at a number of posterior electrodes: (**PO1** [F {1,16} = 4.549, p = 0.05]; **O1** [F {1,16} = 4.889, p = 0.042]; **OZ** [F {1,16} = 5.346, p = 0.034]). In each case the good performance group had higher levels of beta 2. Those electrodes which show significant differences are shown in Figure 7.5.

Figure 7.5 Electrodes showing a difference in beta 2 between good and poor MRT imagers.



7.4 Discussion

In experiment 2 two main predictions were stated:

1. There would be a decrease in EEG power from a baseline to experimental conditions that involved imagery of movement. Moreover, it was anticipated that these changes in the EEG would be dependent on the perspective taken during imagination; the adoption of an external perspective was expected to result in a decrease in power

primarily over the parieto-occipital cortex though changes over the pre-frontal cortex would also be observed. The adoption of an internal perspective was expected to result in a decrease in power primarily over pre-frontal motor areas but also over parieto-occipital areas.

These predictions were not supported by the data. There was no difference between subjects' EEG recorded during the eyes closed baseline and the imagery conditions at any of the electrodes that were examined. In addition no differences were observed between the EEG recorded during internal and external imagery.

2. It was also predicted that there would be a difference in the EEG of subjects classified as good and poor imagers according to both instruments during each of these imagery conditions.

This prediction received partial support. When subjects were classified as good and poor imagers according to their VMIQ score, statistically significant differences between these groups were found over the left frontal region in beta 2. Trends in beta 2 also indicated differences between the groups at pre-frontal and posterior areas of the cortex in both the baseline and the experimental conditions. In alpha, the good imagery group had higher power over both pre-frontal and posterior regions bilaterally. When subjects were reassigned to different groups based on their MRT performance, trends in the data indicated that the good imagery group had higher alpha power over the pre-frontal region bilaterally and over the left parieto-occipital region. The good MRT group also had higher beta 1 over the left occipital region and higher beta 2 over left and central parieto-occipital areas.

If a decrease in alpha is regarded as an index of increased attention, then the relatively lower alpha power observed in the poor (VMIQ) imagery group could be interpreted as showing greater cortical activation in this group during these conditions, reflecting a

higher state of attentiveness. The absence of a condition effect and the failure to observe any differences between the groups in experiment 1 make this explanation unlikely. The experimental conditions were different in each experiment, i.e. subjects had their eyes open during both conditions of experiment 1 and their eyes closed during each condition of experiment 2, so the higher alpha found in the good VMIQ imagery group during experiment 2 suggests that this group has higher levels of endogenous alpha. One might reasonably expect a similar effect when subjects have their eyes open, which was not the case in experiment 1 (though it is always possible that there were differences in attention between the groups during the different conditions in experiment 2). This suggests that the absence of group effect in experiment 1 may have been a result of a decrease in power caused by the eyes being open, though the absence of a significant interaction when subjects are classified according to their VMIQ score does not allow the clarification of this point. However, if one examines the data of subjects classified according to their MRT performance, then this explanation seems plausible.

In experiments 1 and 2 good MRT imagers had higher alpha power over the pre-frontal and parieto-occipital cortex (these differences are not always found at exactly the same electrodes but given the smearing of the signal caused by volume conduction and skull thickness, it is likely that they reflect some of the same underlying activity), so in this group at least the reduction in alpha caused by the eyes being open was not sufficiently great that it masked any differences between good and poor MRT imagers. Given the observed group effect between good and poor VMIQ imagers in experiment 2, the failure to observe a similar effect in experiment 1 may have been a caused by a greater reduction in alpha in the good (VMIQ) imagery group when their eyes were open. If this explanation is correct it would have resulted in a floor effect and the removal of any differences between the good and poor VMIQ imagers and between the experimental conditions. The absence of a comparable decrease in alpha in the good MRT imagery group and the fact these same subjects also had higher power in the baseline condition

over central and left parieto-occipital cortex compared to the poor MRT imagers adds weight to this suggestion.

If this proposal is correct, it could be argued that the decrease in power during the MRT condition found only in the good MRT imagery group but not in the good VMIQ imagery group is merely an artifact resulting from a floor effect being shown in the latter group. Two observations make this suggestion unlikely. First, the decrease in power in the good MRT group during the mental rotation was observed over the parietal cortex bilaterally, whereas the difference between good and poor MRT imagers during the baseline condition was primarily over left and central parieto-occipital cortex. Second, in experiment 2 the good MRT group had higher levels of beta 1 and beta 2 power (primarily over the occipital region) compared to the poor MRT group, whereas no comparable differences were observed in experiment 1. It follows that if there was a floor effect in good (VMIQ) imagers in experiment 1 then by the same token good MRT imagers showed a floor effect in the beta bands in experiment 1. The question would be then raised as to why is there a floor effect only in the beta bands and not alpha in this group? Given the evidence that power in alpha and beta bands exhibit a linear relationship, the eyes open conditions would have produced a decrease in power in all three bands, so if the suggestion of a floor effect is correct then it should have been observed in all three bands.

It is easy to explain away the absence of an hypothesised change in EEG in terms of a floor effect. The evidence of a decrease in power only in the good MRT group and in one frequency band (alpha) during mental rotation (whereas frequency power of both groups decreases as a result of the eyes being open) suggests that there are genuine differences between subjects classified according to objective and subjective measures.

In summary, experimental conditions recorded with subjects' eyes open resulted in a decrease in absolute power in all groups classified either through subjective or objective

assessment. An interaction between imagery ability and a change in EEG from a baseline to an imagery condition was found only when subjects were classified according to an objective measure. The decrease in power in the good imagery group during the MRT demonstrates that the demands of the task are sufficiently high to cause an observable change in EEG activity. This is despite the fact that the EEG power is greatly reduced compared to that recorded in experiment 2. The failure to observe any condition effects or interactions in Experiment 2 is, therefore, a result of the low cognitive demands of the task itself and may possibly be a result of the items chosen from the VMIQ.

One potential weakness in the VMIQ is that some subjects are more adept and experienced at making particular actions and would find it easier to generate the appropriate image. For example, those subjects who have no or little experience of "kicking a ball" are unlikely to have stored representations of themselves performing that action and will, as a result have difficulty in generating the appropriate image. The time since an action was last performed may also affect the richness of its representation and may add further variation to the subjects' ability to generate images. The EEG data recorded during the imagining of these movements was averaged within each subject and so reflects activation associated with familiar and unfamiliar actions. The combination of EEG averaging and experiential effects rather than imagery ability may account for these findings.

It was argued in Chapter 4 (cf. Annett, 1995) that one of the main problems with self rating questionnaires is that there in no way of ensuring that subjects comply with instructions. This may well be true in this experiment, particularly when required to adopt different perspectives. It is possible that on some items of the VMIQ an external perspective is taken even though the instructions are to form an internal perspective. Those actions that require the manipulation of objects (e.g. "catching a ball") involve considerably more visual feedback than those that involve gross body movement and so it is more likely that imagery from an 'internal visual' perspective will be adopted (cf.

White and Hardy, 1995). Thus, even though a kinaesthetic representation is stored in memory what is generated during the imaging of such actions is primarily visuo-spatial in nature. This may not always be strictly a problem of compliance (subjects may attempt to generate a kinaesthetic image but given the perceptual nature of the representation, the generated image is primarily visuo-spatial) it nonetheless constitutes an example of subjects engaging in cognitive activity that is different from what is intended.

Other suggested weaknesses of questionnaires such as the VMIQ include the arbitrary nature of the rating scale and the susceptibility to response bias (Ernest, 1977), the construct of vividness and the likelihood that subjects use different criteria in its assessment. The high reliability of such measures have often been taken to imply their validity but as is seen in this study high correlations of subjective ratings do not necessarily lead to differences in the EEG of those who consistently classify themselves as good or poor imagers. This finding could be interpreted as showing that EEG has limited use as a measure of imagery ability, but previous work has shown it is sensitive to differences in imagery ability (Farah *et al.*, 1988; Marks *et al.*, 1985; Marks and Isaac, 1995).

The results reported here differ to those reported by Marks and Isaac (1995). Their study found significant changes in alpha (an increase in power) only in the high VMIQ imagery group when engaged in movement imagery. There were subtle differences in their experiment and that reported here; subjects in the Marks and Isaac study used only the first four items of the VMIQ and recording procedures (the duration of EEG) was different. This may have accounted for the different results. If this suggestion is correct, it underlines how ambiguous findings often result when different studies adopt different paradigms and procedures.

The validity of vividness questionnaires is still a matter of dispute (Isaac & Marks, 1994) but in the context of this thesis it appears that a failure to observe any condition effects or

interaction in this experiment is due primarily to the adoption of items taken from the VMIQ as an experimental task. An alternative explanation could be that EEG does not have the sensitivity to detect the hypothesised changes, but the observation in experiment 1 that EEG *is* sensitive to performance of an objective imagery task that places high cognitive demands on the subject casts doubt on such a suggestion.

7.5 Conclusion

It is concluded from the first two experiments that there is very little evidence of a relationship between subjective measures of imagery ability (vividness questionnaires) and an objective measure (EEG activity) during a movement imagery task. The lack of any relationship in Experiment 1 is probably due to different processes being involved in movement imagery and imaginary transformation. The absence of any relationship in Experiment 2 is more difficult to explain, though this was probably due to the variability of items in the questionnaire which would confound the nature of the adopted perspective.

However, an objective measure of imagery that presents high cognitive demands provided strong empirical evidence of differences in the EEG of subjects who differ in their test performance. It also provides evidence of focal cortical activation in those subjects who are relatively more adept at such tasks, supporting previous research (Charlot *et al.*, 1992). The study of Charlot *et al.* is important as subjects were classified as good or imagers on the basis of performance on spatial tests and they also used an experimental task that had a high spatial component. Given this finding and the results from the first two experiments it is suggested that any further psychophysiological investigations of dynamic imagery should incorporate objective tasks that are deemed to involve imagery. The adoption of such a task would provide an objective measure controlling for any lack of compliance on the part of the subject and would greatly simplify the interpretation of EEG activity. However, it is important to keep in mind that

given the complexity of the motor system, the use of different imagery tasks are likely to produce different patterns of EEG activity, even though they may be assumed to involve identical cognitive resources. Finally it is suggested that questionnaires may still be thought of as useful instrument when examining task related changes in EEG, but only when the processes involved in this task are similar to those that are involved in the particular questionnaire.

Chapter 8

Are Overt Actions and Movement Imagery Functionally Equivalent?

In experiments 1 & 2, EEG was recorded whilst subjects were performing both objective and subjective tests of imagery. The results showed that the EEG is sensitive to changes in neural activity that occur during the performance of a test (MRT) that produces objective evidence of the use of imagery, but not during the performance of a task which produces subjective evidence of imagery (VMIQ). They also showed that there are differences in the neural activity of subjects classified as good and poor imagers based on

objective and subjective measures, but that these differences depend on the experimental conditions during which the EEG was recorded. In experiment 1, differences were observed in the EEG of subjects grouped according to their performance on the MRT but not when they were grouped according to subjective assessment (VMIQ). In experiment 2 there were differences in the EEG of those same subjects classified on the basis of their score on the VMIQ.

Although this latter finding is interesting, the most important aspect of experiment 2 was the absence of any main condition effect or interaction. This suggests either that the EEG is not sufficiently sensitive to changes in cortical activity that occur *during* the generation, inspection and assessment of images, or that items taken from subjective measures like the VMIQ do not have a sufficiently high cognitive load to produce observable changes in neural activity. A third explanation could be that self assessment of the vividness of an image bears little or no relation to the subjective richness and clarity of the underlying representations. As noted previously, this type of instrument has been reported to be subject to response bias and other demand characteristics (Ernest, 1977) and may also suffer from a lack of subject compliance (cf. Annett, 1995). Although some studies have been able to demonstrate that vividness scores can predict performance on tasks requiring imagery (e.g. Finke, 1979), there is still a debate concerning the validity of such measures. The first alternative is unlikely given the evidence from experiment 1 and other studies (see section 3.3) that EEG is sensitive to imagery based tasks. It is suggested that the most plausible explanation for these findings is a combination of the low cognitive demands of the task using items taken from the VMIQ and the questionable validity of the questionnaire itself.

It was decided that a further two experiments would continue to investigate cortical changes associated with movement imagery but would involve a test of movement imagery known to produce specific behavioural effects. The two experiments were also designed to investigate, using psychophysiological methods, the distinction between the

internal and external perspective which supposedly activate kinaesthetic and visual representations respectively (Mahoney & Avener, 1977). With regard to individual differences, it was decided that an additional subjective measure of imagery vividness that controls for experiential effects should be used in addition to the MRT and VMIQ. To that end, an adapted version of the MIQ (Hall, Pongrac & Buckolz, 1985) was administered, as it requires subjects to first make a particular movement and then generate and rate the vividness (both visual and kinaesthetic) of the appropriate image.

8.1 Experiment 3

8.1.1 Introduction

This study adopted a Short Term Motor-Memory (STMM) paradigm as a method of measuring the effects of movement imagery on performance. A typical experiment comprises a linear positioning task in which subjects have to move their hand and arm from a fixed start to a criterion position and then attempt to reproduce it by making another movement which is either of the same distance and/or to the same end location. If memory of location is being investigated, then the starting point in the recall condition is different from that used in the learning condition but the end point remains the same. If memory of distance is being investigated, then a different start and end point are used during recall but subjects attempt to make a movement of the same length to that learned previously.

A distinction is often made between movements that are passive and active and between those that are self-selected and constrained. A movement is active if the subject initiates the movement to a criterion position but passive if the experimenter moves the subject's arm. A movement is self selected if the subject initiates the end point of a movement but is constrained if the end point is determined by the experimenter. Different combinations of these variables affect STMM. In this experiment active constrained movements are

made; the subject produces a movement to an end position which was determined by the experimenter.

Investigations of the underlying representations (cognitive structures and the processes acting upon them) involved in such task have tended to use the 'structural interference paradigm' which incorporates an additional task thought to engage similar or different processes to the task under investigation. In a typical experiment this additional movement task is interpolated between the criterion acquisition and reproduction movements, a common observation being that when the interpolated movement is different in length to the criterion, it results in a distortion of the criterion movement in the direction of the interpolated movement. That is, when it is longer than the criterion subjects tend to overestimate the reproduction (Adams & Dijkstra, 1966; Laabs, 1973; Patrick, 1971; Stelmach & Walsh, 1973).

In an interesting adaptation of this paradigm, Johnson (1982) included the imagination of movement as the interpolated task and found that recall of a previously learned movement was biased in the direction of the imagined movement, i.e. subjects tended to overestimate or underestimate distance depending on the length of the imagined movement. Moreover, the bias in recall was similar to that produced when subjects actually made an interpolated movement equal in length to the imagined movement. In a series of follow up experiments, Johnson demonstrated that the performance of a concurrent visuo-spatial task during the retention interval, but not a concurrent motor task, resulted in the removal of this interference effect. This showed that imagery in this experiment comprised primarily visuo-spatial representations and although instructed to imagine themselves making the movement, it is likely that subjects adopted an 'internal visual' perspective (see chapter 2). The results of Johnson are important as they provide the strongest evidence in the research literature of complete functional equivalence between the overt action and imagery of movement. They are also important as they demonstrate that as well as having a motor component, the linear positioning task and the

type of dynamic imagery used by subjects, may involve visual or visuo-spatial representations.

In experiment 1 no relationship was found between the VMIQ and MRT, a result probably of the fact they involve different forms of dynamic imagery. In experiment 2 the question was raised whether variability in subjects' experience of making the movements described in the VMIQ may have been a confounding factor. To control for this factor it was decided to introduce the Movement Imagery Questionnaire (MIQ) as an additional measure of vividness. If this is an important factor then the MIQ should demonstrate a stronger relationship than the VMIQ to recall on the linear positioning task following the interpolated imagery task. Scores from different questionnaires have been found to correlate with another (cf. Kihlstrom. Glisky, Peterson, Harvey & Rose, 1991) so it was decided to examine the relationship between the two subjective measures used in this experiment. The relationship between these measures and the MRT was also examined as a means of replicating the result of experiment 1.

The procedure used in experiment 3 was adapted from the task used by Johnson (1982). The EEG was recorded during a linear positioning task in which subjects were required to learn a movement to a particular position, perform an interpolated task and then attempt to reproduce the original movement. In Johnson's experiment subjects timed their movements according to an external timing mechanism but this was thought to be inappropriate as it would introduce considerable 'noise' into the EEG. The movements in this study were, therefore, self-paced. On the basis of Johnson's results a number of predictions were made:

Behavioural Predictions

1. Interpolated activity consisting of either the actual production or the imagination of a movement half the length of previously learned movement would lead to the

underestimation of the movement during recall. In contrast no such bias in recall would occur when the interpolated activity consisted of subvocally counting backwards in threes.

2. It was also predicted that the *imagination* of a movement of different extent to the criterion movement would result in significantly lower variability in recall compared to the *actual production* of a movement different in extent to the criterion movement.

3. MRT would demonstrate a stronger relationship than either the VMIQ or MIQ to performance on the linear positioning task. Furthermore, if subjects' experience at making movements is an important factor then the MIQ should exhibit a stronger relationship to performance on the linear positioning task than the VMIQ. If experience at making particular movements does *not* affect the rating of movement imagery, then there should be a relationship between the VMIQ and MIQ.

4. Finally given the previous finding that MRT performance and VMIQ scores are not related, no relationship was expected between the two questionnaires and MRT performance.

Psychophysiological Predictions

It has been argued in previous chapters that the pre-frontal cortex has an important role in the attentional mechanisms controlling the planning and temporal organisation, and that it is involved in the planning and control of movement images. These areas were expected to be involved in the imagination of movement in this experiment

The parietal lobe has been shown to be important in visually guided movement (Kalaska & Crammond, 1992; Taira *et al*, 1990) and the parieto-occipital region has been shown to be active during the generation and manipulation of dynamic imagery that has a large spatial component (Charlot *et al*., 1992; Deutsch *et al*., 1988; Peronnet & Farah, 1988;

Roland & Friberg, 1985). It has also been demonstrated that the planning of movement has a large spatial component (Quinn & Ralston, 1986), that the linear positioning task has a large spatial component (Laabs, 1973) and that the adoption of a 'visual internal' perspective during imagery involves visuo-spatial processing representations (Johnson. 1982). Taken together this research suggests that the parieto-occipital region will play an important role in the task used in this experiment.

With regard to the question of individual differences, Smyth *et al.* (1988) and Smyth and Pendelton (1989) have proposed that information of whole body movement is configured differently to that related to accurate movements to targets in space. Although the VMIQ and MIQ assess the vividness of movement images *per se* these questionnaires do not differentiate between gross body movements and those that require accurate movement of limbs to various points in space. Although these questionnaires examine movement imagery it is unclear whether they are able to predict changes in the EEG that are related to the kind of movement imagery used in this experiment. Given the predominantly spatial nature of the MRT and the results from experiments 1 and 2, demonstrating that objective tests rather subjective assessment provide observable changes in the EEG, it was expected that this measure in particular would be related to performance on this task and to the EEG activity recorded during imagery.

On the basis of this research a number of predictions were stated:

1. There would be a reduction in EEG power density (see Chapter 5) in the alpha and beta frequencies over pre-frontal and parieto-occipital cortex, during movement imagery compared to an eyes open baseline.

2. If some form of functional equivalence exists between imagery of movement and overt action, then there would be comparable levels of cortical activation recorded during

imagery and actual movement over areas of the cortex thought to be involved in those high level cognitive aspects of motor control i.e. the pre-frontal cortex.

3. Individual differences in imagery ability would predict the degree of change in EEG activity from a baseline to the imagery condition, at the cortical areas referred to above. The clearest example of this relationship would be based on objective performance (MRT) rather than on subjective assessment (VMIQ and MIQ).

8.1.2. Method

Subjects

24 right handed subjects (16 male, 8 female) aged 21 - 34 (mean age 24.87 years) were selected from the research staff at the Defence Research Agency, Centre of Human Sciences, Farnborough. The EEG data of two of these subjects was found to be corrupted and they were not included in any analysis. The remaining 22 subjects (15 male, 7 female) had a mean age of 24.13 years.

Apparatus and Materials

Subjects completed the Vandenberg and Kuse (1978) Mental Rotation Test (MRT) and two questionnaires; the Vividness of Movement Imagery Questionnaire (VMIQ) (Isaac *et al.*, 1986) and a modified version of the Movement Imagery Questionnaire (MIQ) (Hall *et al.*, 1985). The original MIQ comprises 18 items that assess the vividness of kinaesthetic and visual imagery. Subjects first perform the movement and then rate the vividness (on a scale of 1 = a clear and vivid image, to 7 = no image at all) of both a visual and kinaesthetic image of themselves performing the action. The modified version used in this study consisted of 8 statements taken from the MIQ; the number of items was reduced as some of the actions in the original were considered inappropriate for a

laboratory based experiment using non-athletic subjects. A 5 point scale was also introduced to provide some consistency between this measure and the VMIQ. The procedure set out in the original questionnaire was adopted in this modified version. See Appendix B.

The experimental apparatus comprised a plastic linear slide 140 cm x 2.8 cm x 0.8 cm mounted on a horizontal wooden base 150 cm in length. A handle consisting of a cylindrical knob 1.5 cm height and 1.5 diameter built on steel block 12.5 cm x 6 cm x 2.5 cm was free to move along the track. A pointer aligned to a millimetre scale obscured from the subjects' view was attached to one side of the handle. Two adjustable stops allowing changes in the track length were placed either side of the handle. The experimental apparatus was placed on a table 75 cm high and positioned at right angles to the subjects' field of vision. See Appendix C, Figure C8.1.

Procedure

In this chapter, 3 terms (session, condition and trial) are used to denote the different elements of the experiment. There were 3 experimental sessions each consisting of an acquisition, interpolation and recall condition. In the acquisition condition subjects received 15 learning trials. The interpolated condition differed in each session; subjects either physically made movements, imagined making movements or counted backwards in threes. The duration of each interpolated condition was one minute. In the recall condition subjects made 15 attempts at recalling the criterion position learned during acquisition. See Table 8.1.

Baseline Condition

EEG was recorded during a baseline (eyes open) condition for two minutes. Subjects were instructed to relax physically and mentally and keep as still as possible while fixating on a point on the wall immediately in front of them. They were also requested to

keep eye blinks to a minimum and to keep the mouth slightly open to reduce jaw muscle artifact.

Acquisition condition

Subjects held the handle with their right hand and were required to move it from left to right to a stop point that had been set by the experimenter. On reaching the stop point they briefly released the handle before grasping it again and returned to the start point. All subjects received 15 trials, each movement being *self paced*. The subjects were able to see all the apparatus with the exception of the mm scale measure used for scoring. They were instructed to gaze at the apparatus and to attend to their hand as it moved along the track, but without moving their eyes or head.

Interpolated condition

The 3 different forms of interpolated activity were:

Novel Actual Movements (NAM)

Subjects held the handle with their right hand and were required to move it left to right from the same starting point to a different stop point, set by the experimenter at half the distance of the original movements. On reaching the stop point they briefly released the handle before grasping it again and returning to the start point. Subjects were instructed to make the movements at the same speed used in the acquisition condition and to repeat the movements until they were told to stop by the experimenter.

Novel Imaginary Movements (NIM)

Subjects were required to sit with their arms at their sides and imagine making a movement that was half the length of the criterion movements. They were instructed to imagine making the movements at the same speed used in the acquisition trials and to

continue to imagine these movements until they were told to stop by the experimenter. All subjects had their eyes open during this condition.

Counting Backwards (CON)

Subjects were instructed to count backwards in threes subvocally from a starting point of 359 until told to stop by the experimenter.

Recall condition

Subjects were required to recall the movement learned during the acquisition condition but with the stop removed. They were instructed to move the handle to where they thought the original end point had been, briefly release the handle before grasping it again and returning to the start point. All subjects received 15 recall trials, each movement being self paced. Each recall trial was scored for magnitude of error from the criterion position taking note of the error to the nearest 0.5 cm.

The procedure was repeated for each type of interpolated activity with a 5 minute delay between each session. The combination of the different movement lengths and interpolated activities is presented in Table 8.1.

Table 8.1 Details of the distance learned in the acquisition condition and the different interpolated activities used in each session.

Movement session	Acquisition	40 cm	Stop
	Novel Actual Movement	20 cm	Stop
	Recall		No Stop
Control Session	Acquisition	45 cm	Stop
	Counting Backwards		No Movement
	Recall		No Stop
Imagery Session	Acquisition	50 cm	Stop
	Novel Imaginary Movement		25 cm
	Recall		No Stop

The order of presentation of each session was counterbalanced across subjects.

Apparatus and EEG Recording

The EEG equipment and recording settings are described in chapter 5.

8.1.3 Results

8.1.3.1 Behavioural data

As the recall condition required 15 reproductions of a previously learned movement the difference between the reproduction and criterion movements was recorded to provide an error score for each subject. There are three ways in which an error score can be calculated:

1. Constant Error (CE)

This measures the magnitude but takes into account the sign of the error and providing an estimate of directional bias in recall.

2. Variable Error (VE)

This measure the consistency of the recall movements and is usually calculated as the standard deviation around the mean for each subject. This provides an estimate of the strength of the memory trace in terms of the consistency of reproduction.

3. Absolute Error (AE)

This measures the magnitude of the error (irrespective of the sign) for each recall trial which is then averaged over the number of reproductions. This method has been criticised (Schutz & Roy, 1973) as it is a function of CE and VE, i.e. when CE is zero VE and AE provide identical information but if CE is not zero then AE is a function of CE and VE. As this study is concerned primarily with the directional bias and with the variability of recall the dependent variables used in analysis are CE and VE.

8.1.3.1a Constant error

A summary of the mean and standard error of CE are shown in Table 8.2. The mean CE in both the movement and imagined movement session show that subjects tended to overestimate the extent of the criterion movement. Only the interpolated activity in the control session led to a negative bias in recall, though this effect was small. The effects of the different types of interpolated activity on constant error is shown in Figure 8.1.

Figure 8.1 Mean Constant Error of recall of the criterion movements following the different types of interpolated activities

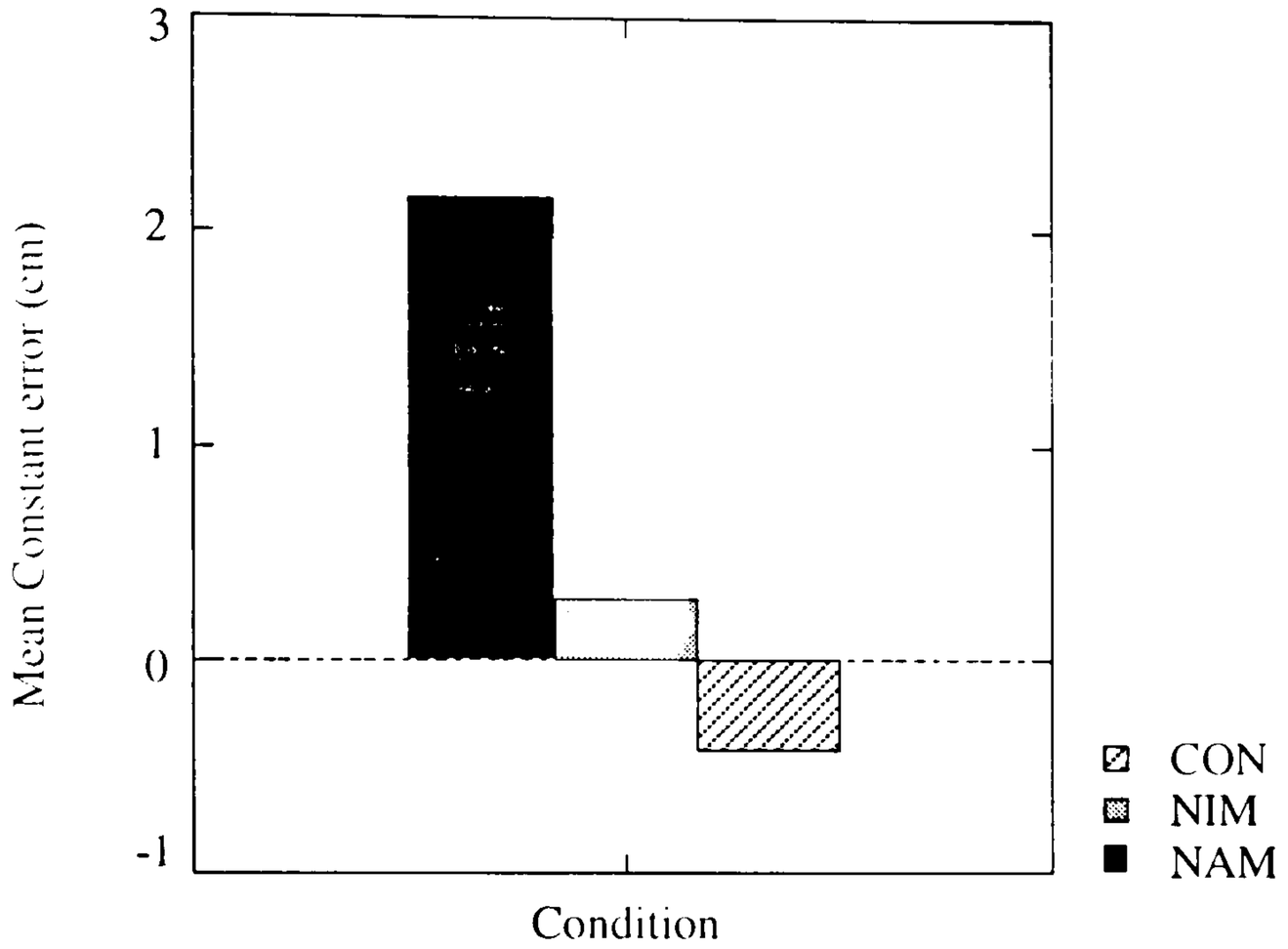


Table 8.2 Summary of mean (X) and standard error (SE) of constant error (CE)

		NAM	NIM	CON
CE	(X)	2.174	0.280	-0.420
	(SE)	1.079	1.041	0.909

NAM = Novel Actual Movement
NIM = Novel Imaginary Movement
CON = Control

A one way ANOVA using constant error as the dependent variable showed a non significant effect for type of interpolated activity, $F(2,42) = 2.303$, $p > 0.05$.

8.1.3.1b Variable error

The constant error (VE) scores were calculated from the raw data. A summary of the mean and standard error of VE are shown in Table 8.3. It is clear that there is very little

difference in the mean VE of each session. The effects of the different types of interpolated activity on VE is shown in Figure 8.2.

Figure 8.2 Mean Variable Error of recall of the criterion movements following the different types of interpolated activities

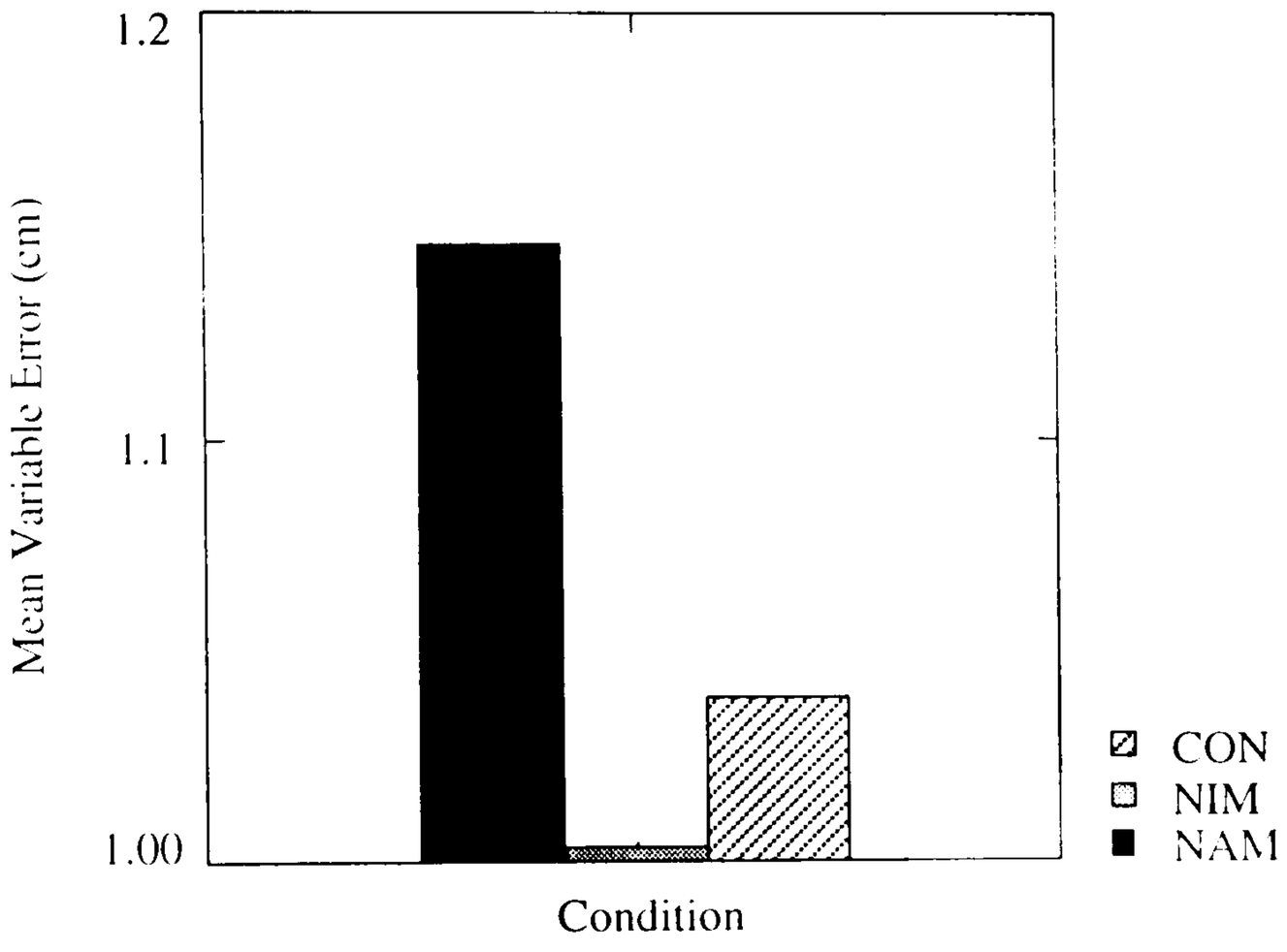


Table 8.3 Summary of mean (X) and standard error (SE) for variable error (VE)

		NAM	NIM	CON
VE	(X)	1.147	1.004	1.038
	(SE)	0.194	0.186	0.130

NAM = Novel Actual Movement
NIM = Novel Imaginary Movement
CON = Control

A one way ANOVA using constant error as the dependent variable also showed a non significant effect for type of interpolated activity, $F(2,42) = 0.233$, $p > 0.05$.

8.1.3.1c Individual Differences

The means and standard deviations of the VMIQ, the MIQ and the MRT are presented in Table 8.4. The mid point of the VMIQ and MIQ are 144 and 48 respectively (72 and 24 for the sub-scales). As low scores on both questionnaires indicate vivid imagery, it is apparent from Table 8.4 that most subjects reported that their images were at least moderately clear and vivid (a rating of 3 or less on the scale). The mid point of the MRT is 10 so it is also appears that on average subjects perform above this level.

Table 8.4

Summary of means and standard deviations of the VMIQ, MIQ and MRT.

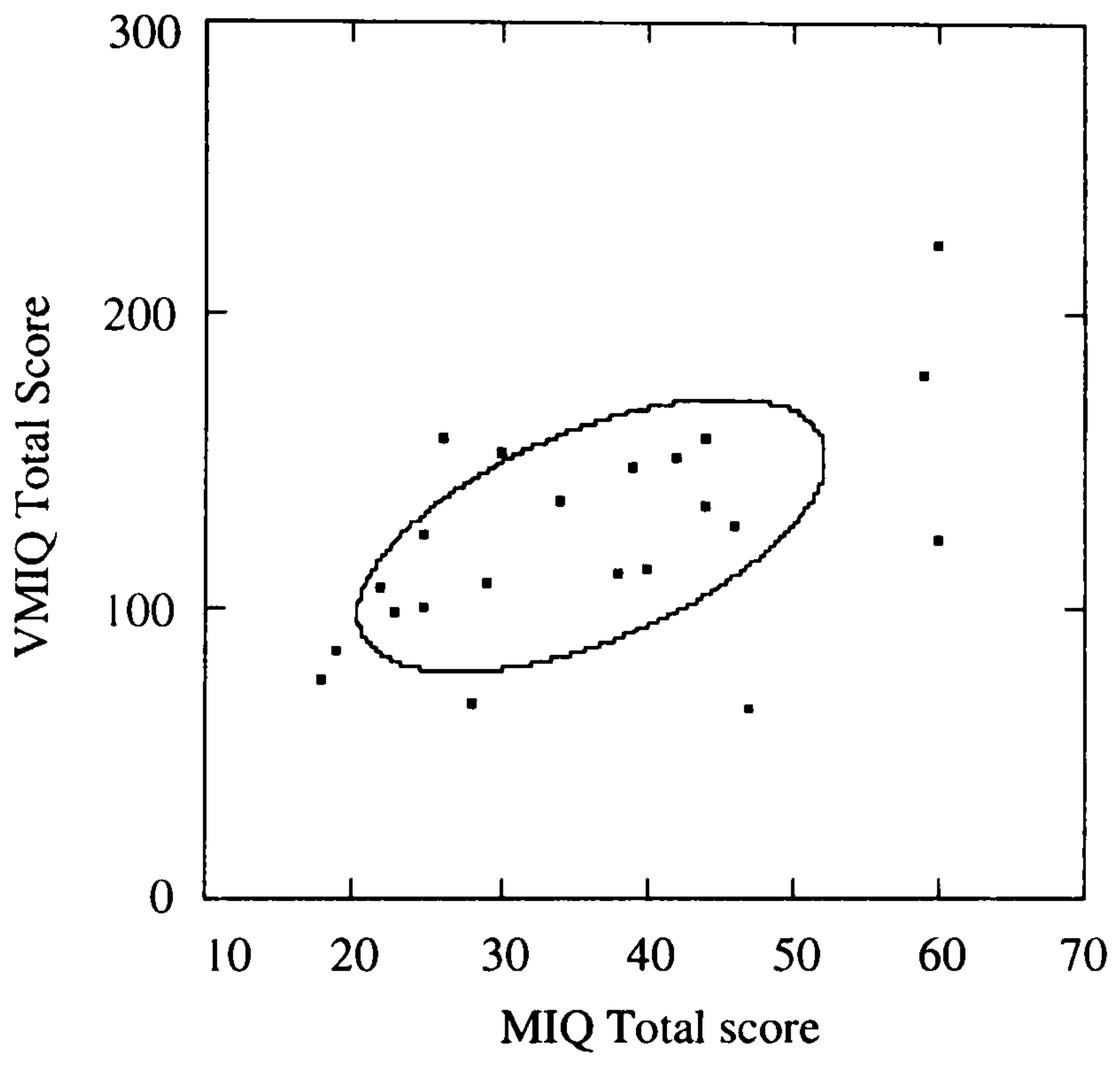
	VMIQ__T	VMIQ_K	VMIQ_V	MIQ_T	MIQ_K	MIQ_V	MRT
Mean	124.85	62.91	63.01	36.27	18.14	17.68	13.59
SD	38.36	19.22	21.91	13.08	6.72	6.69	5.82

T = Total
K= Kinaesthetic Imagery Score
V = Visual Imagery Score

To test whether any of these measures predicted recall of the criterion movement following the novel imaginary movement (NIM), a multiple regression analysis was performed using the total scores on both questionnaires and MRT performance as independent variables and mean constant error from the imagery session as the dependent variable. None of these measures significantly predicted constant error scores on the linear positioning task, $F(3,18) = 1.764$, $p > 0.05$. Multiple regression analysis was also performed using mean variable error as the dependent variable; none of the measures predicted variable error scores. $F(3,18) = 1.748$, $p > 0.05$.

A series of correlations using the Pearson product moment coefficient were performed between the VMIQ, MIQ and MRT. No relationship was found between performance on the MRT and self report imagery ability according to the VMIQ ($r = 0.076$, $p > 0.05$) or the MIQ ($r = 0.057$, $p > 0.05$). A highly significant relationship was found between the VMIQ and the MIQ, ($r = 0.575$, $p < 0.005$). See Figure 8.3

Figure 8.3 Pearson Correlation showing relationship between Total scores of VMIQ and MIQ

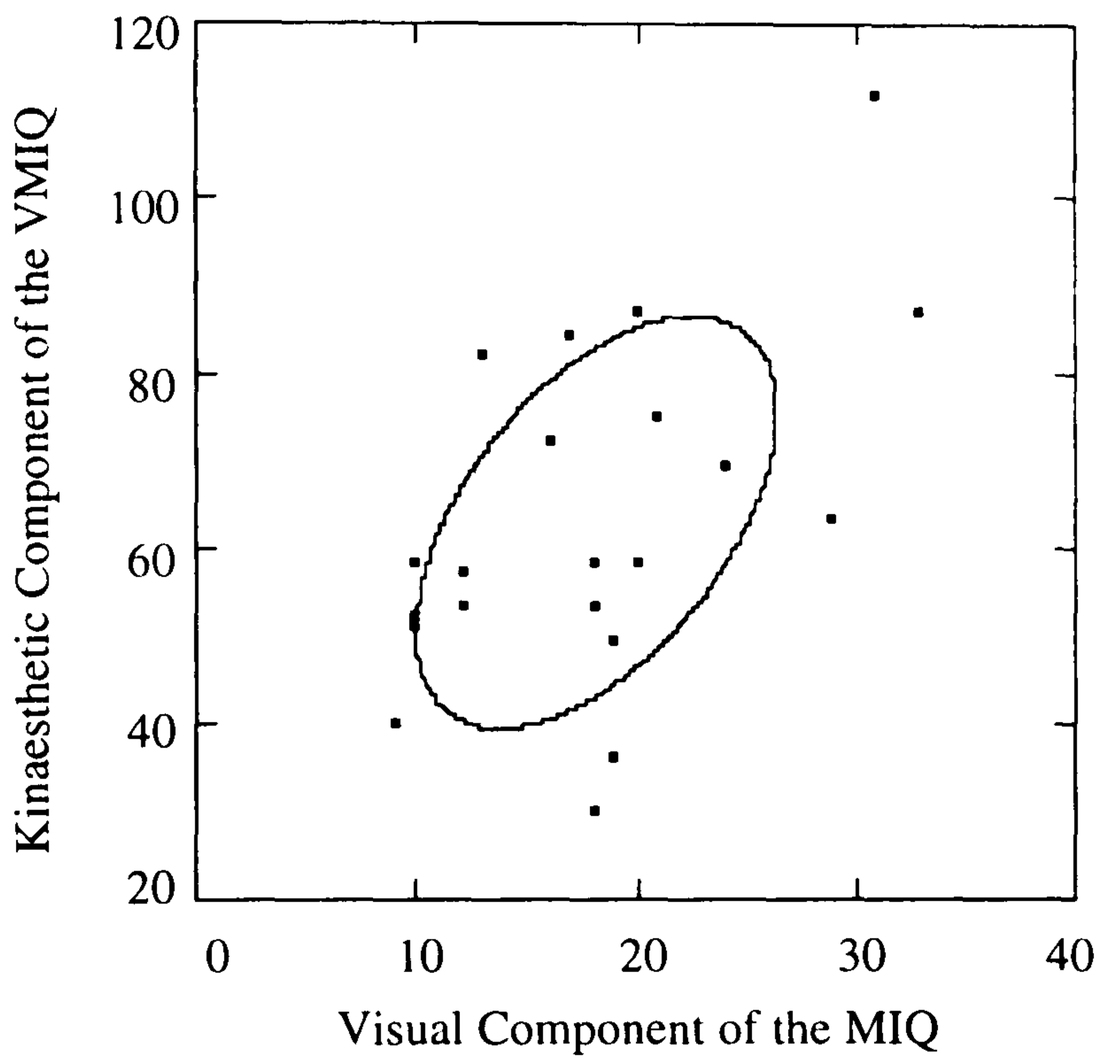


The above figure demonstrates that there is a strong positive relationship between the two questionnaires, showing that subjects were consistent in how they rated the vividness of images taken from the VMIQ and MIQ.

Given the strength of the relationship between the total scores of each questionnaire, it is perhaps not suprising to find that there were strong correlations between the visual imagery and kinaesthetic components of each individual questionnaire: VMIQ ($r = 0.868$, $p = 0.0005$), and MIQ ($r = 0.689$, $p = 0.0005$). An examination of the relationship between the sub-scales of the VMIQ and the MIQ showed a significant positive

correlation between the visual components of each questionnaire ($r = 0.563$, $p < 0.006$) but not between the kinaesthetic components ($r = 0.20$, $p > 0.05$). There was a positive correlation between the kinaesthetic and visual components of the VMIQ and MIQ respectively,($r = 0.534$, $p < 0.01$). See Figure 8.4.

Figure 8.4 The relationship between the kinaesthetic component of the VMIQ and the visual component of the MIQ



The vividness ratings on visual imagery scale (MIQ) increase so too do the ratings of the kinaesthetic imagery (VMIQ), suggesting perhaps that representations of movement images are comprised both of visual and kinaesthetic information.

8.1.3.2 Psychophysiological data

As the EEG recorded during the mental imagery session is of primary interest, only these data together with the EEG recorded during the baseline condition will be presented. The raw EEG and EOG trace was recorded during each trial of each condition and was visually inspected for artifact due to eye movement and muscle contamination. Although

the movements made in this study were relatively simple with few degrees of freedom, it is inevitable that some muscle related artifact be present in the EEG. However, close inspection of the raw EEG trace, particularly during the trials that involved actual movement, showed that there was not as much muscle contamination as was expected. Presumably, this was a result of the few degrees of freedom required in the movement. Where there was evidence of gross muscular activity, these data were excluded from any further analysis. If an individual channel was found to be noisy during any of the trials then it was excluded from any further analysis. A minimum of 10 artifact free epochs from each subject in each condition was used in the analysis. The mean duration of artifact free data across all subjects was 28 epochs (56 secs) for the eyes open baseline, 21 epochs (42 secs) for the acquisition condition, 20 epochs (40 secs) for the mental imagery condition and 19 epochs (38 secs) for the recall condition.

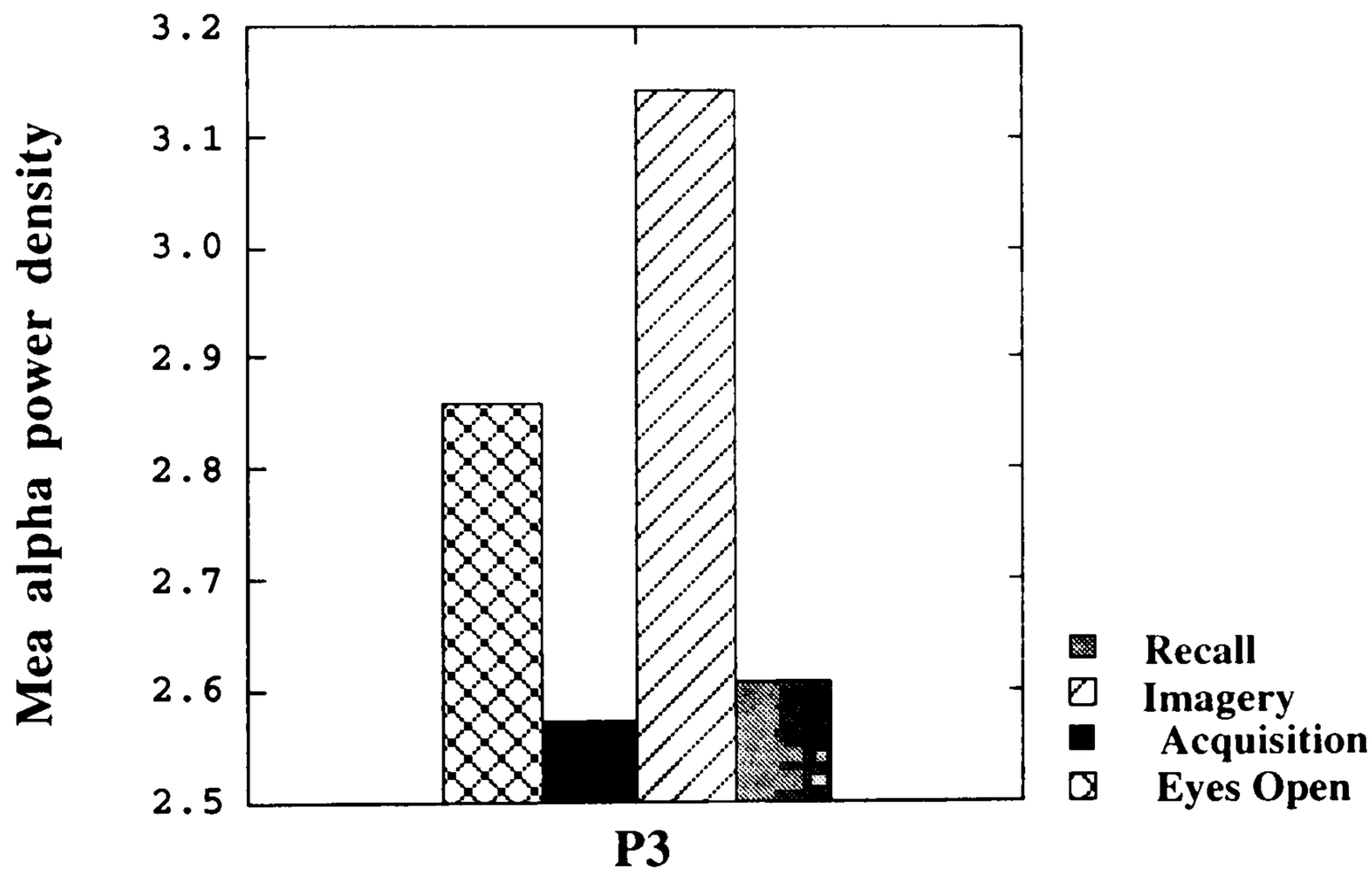
Given the hypotheses stated set out in 8.1.1 the data from five anterior electrodes (F3, Fz, F4, F7 and F8) and eight posterior electrodes (T5, P3, Pz, P4, T6, O1, Oz and O2) were downloaded for more detailed analysis. Additional occipito-parietal variables (P3O1, P4O2) were derived by calculating the mean power density at these sites [e.g. P3O1 = (P3 + O1) /2]. Output from the imager provided spectral power values (μV^2) in bins of 0.5 Hz and from these power density values (μV^2/Hz) were calculated in the alpha, beta 1 and beta 2 frequency bands (see Chapter 5). The data in all 3 frequency bands were found to be skewed and were log transformed prior to further analysis to normalise their distributions.

MANOVAs were conducted with condition (eyes open x acquisition x novel imaginary movement x recall) and site (the 15 electrodes specified above) as variables, followed by repeated measures univariate ANOVAs and the appropriate post hoc tests. This was followed by regression and correlational analysis described in Chapter 5.

Alpha

The means and standard deviations of power density at each electrode in the alpha frequency band during each of the four conditions are presented in the Appendix A, Table A8.1 This table shows that at most of the electrodes, there is lower power density (greater activation) during acquisition (ACQ) and recall (REC), i.e. those conditions that involved actual movement. It also shows that there is little difference in the EEG recorded during eyes open (EO) and mental imagery (MI). The mean power density at P3 is presented in Figure 8.5 to illustrate this point.

Figure 8.5 Power Density recorded at P3 during all four conditions

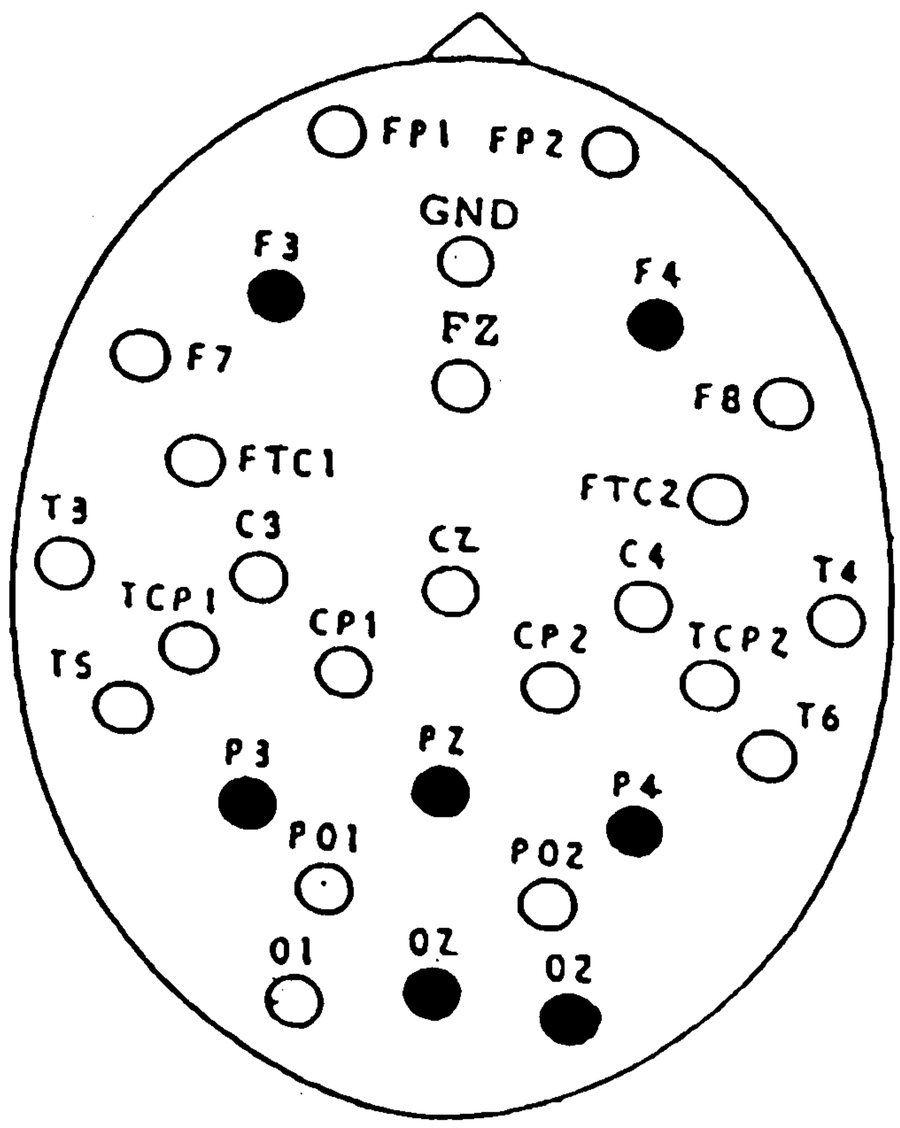


MANOVA indicated a significant effect of condition [F (3, 19) = 79.088, $p < 0.0005$]. Repeated measures ANOVAs were performed on data recorded at each electrode during each type of condition. Significant effects were found at a number of sites, the details of which are summarised in Table 8.5. Those electrodes which show significant differences are shown in Figure 8.6.

Table 8.5 Electrodes at which main condition effects were observed in alpha

Electrode	d.f.	F-ratio	p
F3	3,63	4.00	0.01
F4	3,63	3.58	0.02
P3	3,63	7.15	0.001
Pz	3,63	10.59	0.0001
P4	3,63	4.78	0.01
Oz	3,63	4.38	0.01
O2	3,63	3.16	0.05
P4O2	3,63	3.23	0.046

Figure 8.6 Figure showing location of main condition effects in alpha



A summary of the post hoc analysis is presented in Table 8.6

Table 8.6a Electrodes demonstrating a change in alpha from the eyes open baseline to the acquisition (learning) condition

Electrode	Conditions	p (Tukey)
P3	EO - ACQ*	0.05
Pz	EO - ACQ*	0.001
Oz	EO* - ACQ	0.0002
O2	EO* - ACQ	0.024

Table 8.6b Electrodes demonstrating a change in alpha from the eyes open baseline to the recall condition

Electrode	Conditions	p (Tukey)
Pz	EO - REC*	0.02

Table 8.6c Electrodes demonstrating a change in alpha from the imagery condition to the acquisition (learning) condition

Electrode	Conditions	p (Tukey)
F3	MI - ACQ*	0.007
F4	MI - ACQ*	0.03
P3	MI - ACQ*	0.001
Pz	MI - ACQ*	0.0003
P4	MI - ACQ*	0.005

Table 8.6d Electrodes demonstrating a change in alpha from the imagery condition to the recall condition

Electrode	Conditions	p (Tukey)
F4	MI - REC*	0.03
P3	MI - REC*	0.004
Pz	MI - REC*	0.002
P4	MI - REC*	0.01

* indicates lower power density ($\mu V^2/Hz$) during that condition

EO = Eyes Open Condition MI = Mental Imagery Condition
REC = Recall Condition ACQ = Learning Condition

In summary, Table 8.6 shows that there was lower power density in those conditions that involved movement, i.e. ACQ and REC, compared to the EO and MI conditions. The only difference between EO and MI was found at Oz; there was lower power density during the baseline condition than during the imagery condition. No differences in power density were observed between ACQ and REC

Following the regression procedures described in chapter 4 it was found that only MRT performance consistently predicted any change in EEG recorded during the different conditions of the mental imagery session. Specifically, MRT predicted a change in power density from the EO to the MI condition. A summary of the results from the regression analyses is presented in Table 8.7.

Table 8.7

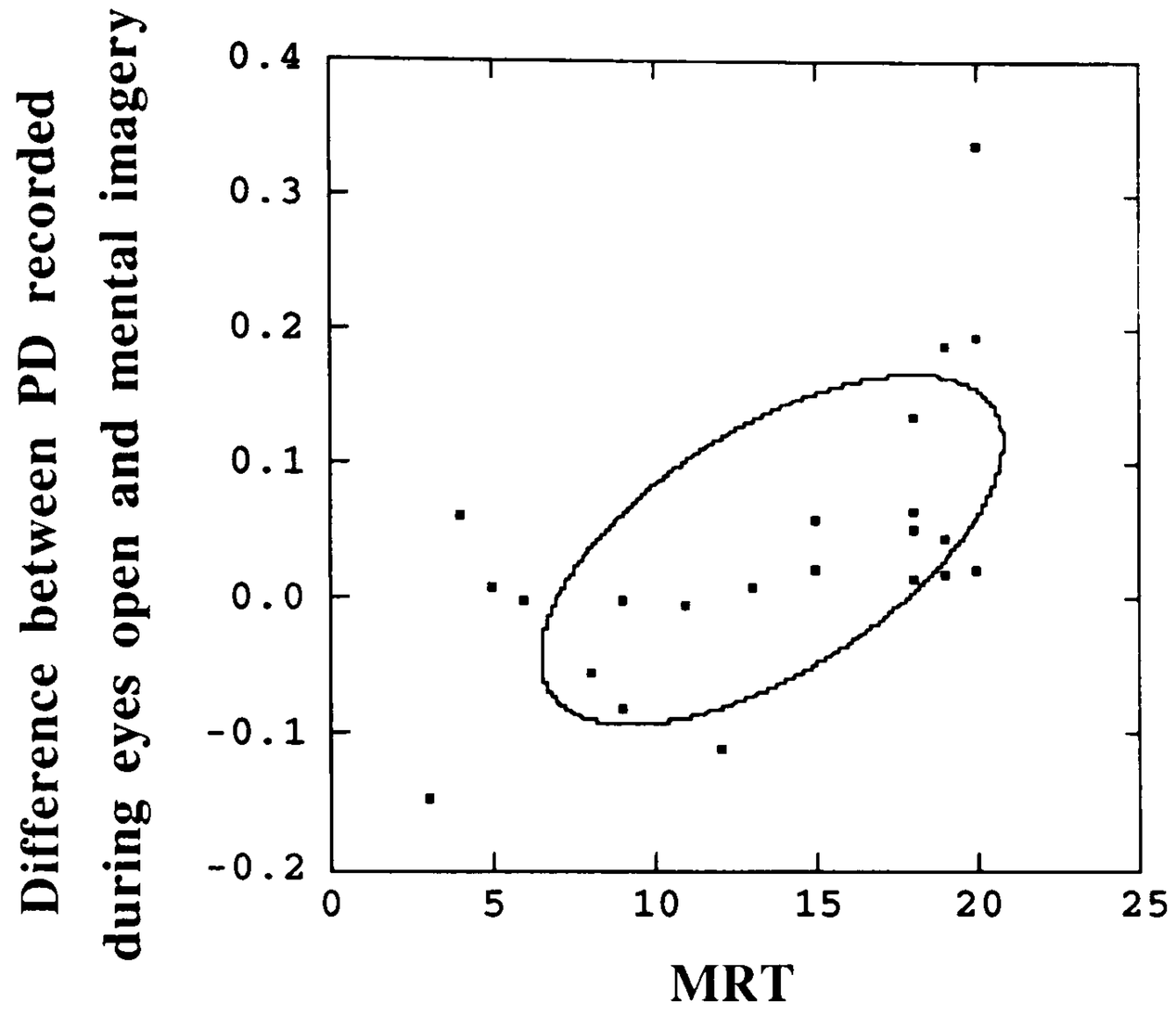
Summary of Multiple Regression analyses showing that MRT performance predicts changes in alpha from the Eyes Open baseline to the Imagery condition

	Coefficient	t	p	Spr (%)
O1	0.0029	4.48	0.0001	42
Oz	0.0023	3.45	0.004	30
O2	0.0028	2.98	0.009	24

Spr = Semi-partial correlation coefficient

Table 8.7 demonstrates that positive relationships between MRT performance and changes in EEG power density were observed only observed at occipital sites. An example of this relationship is presented in Figure 8.7.

Figure 8.7 The relationship between MRT performance and the change in EEG from a baseline to the imagery condition



An examination of Appendix Table A8.1 shows that there is higher power density in the MI condition, so this relationship implies that as MRT performance improves, the difference in power density between the two conditions increases . To examine the relationship of MRT to EEG recorded during EO and MI, Pearson correlations were performed between the MRT data and the EEG recorded during each of these conditions at the sites reported in Table 8.7. Results showed that there was a significant correlation between MRT performance and EO baseline EEG at left and central occipital sites: O1 ($r = -0.55$, $p = 0.008$) and Oz ($r = -0.45$, $p = 0.03$), but not between MRT performance and EEG activity recorded during the imagery condition. See Figures 8.8 & 8.9.

Figure 8.8 Correlation of alpha Power Density at O1 with MRT performance

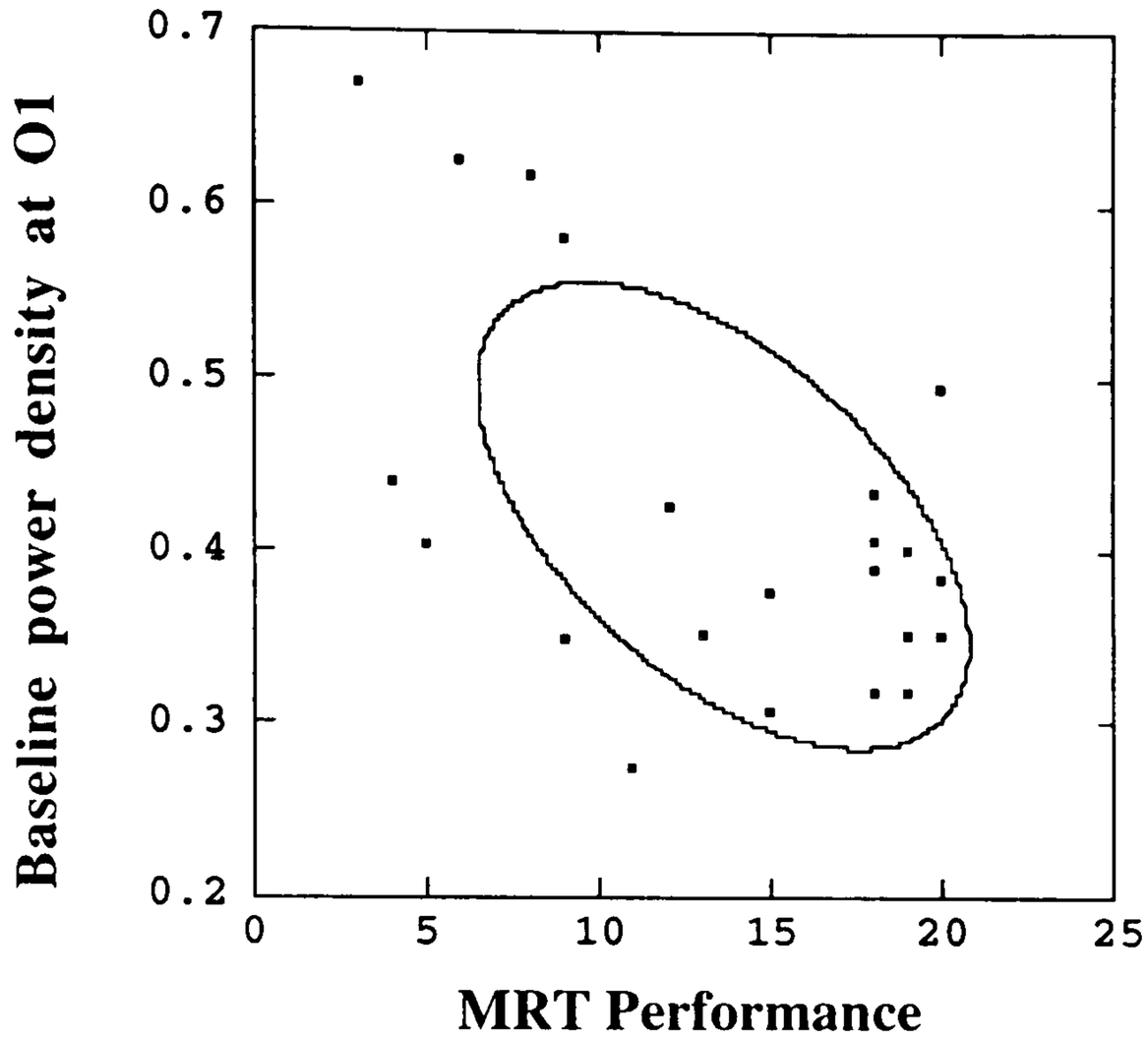
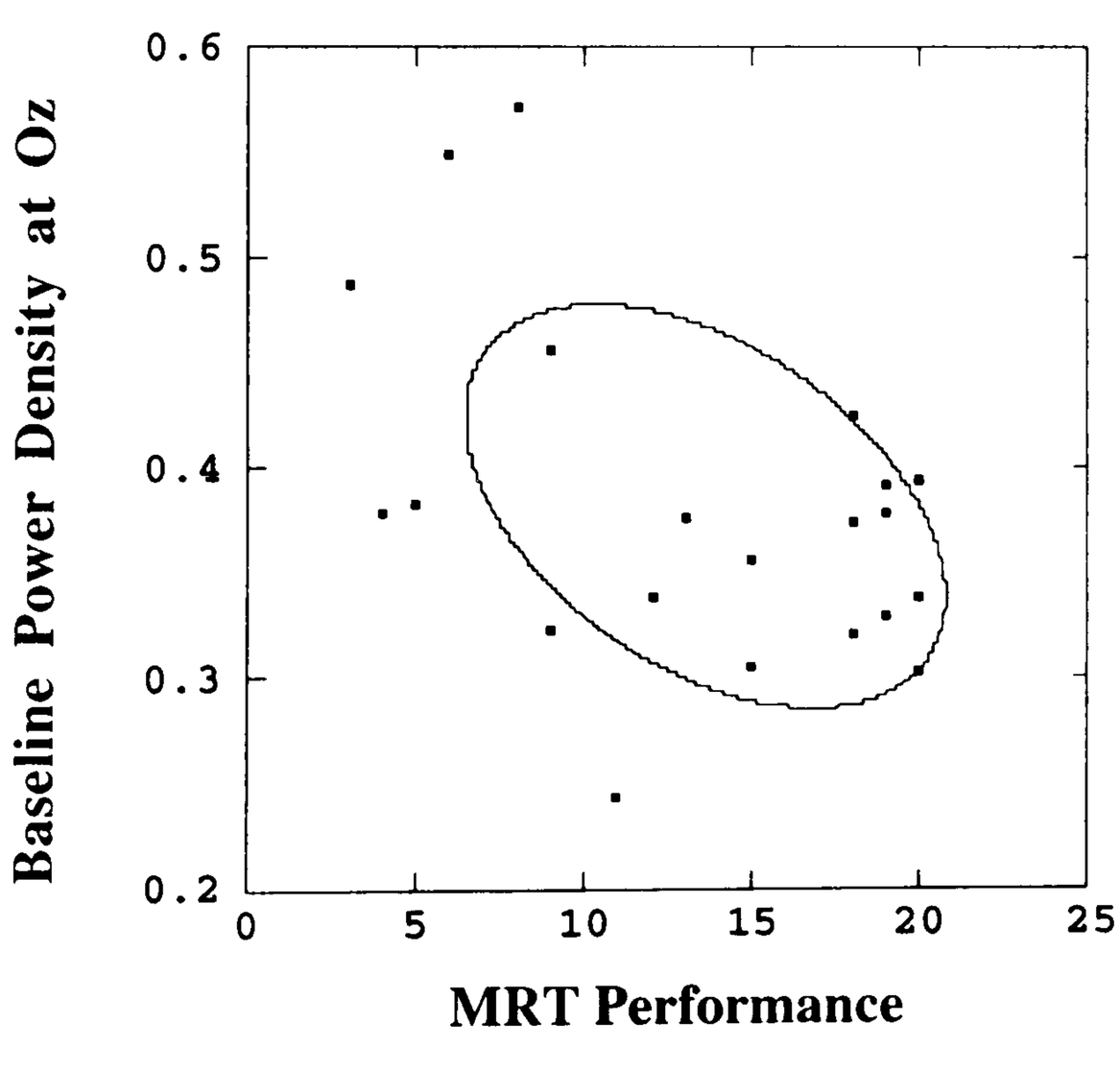


Figure 8.9 Correlation of alpha Power Density at Oz with MRT performance



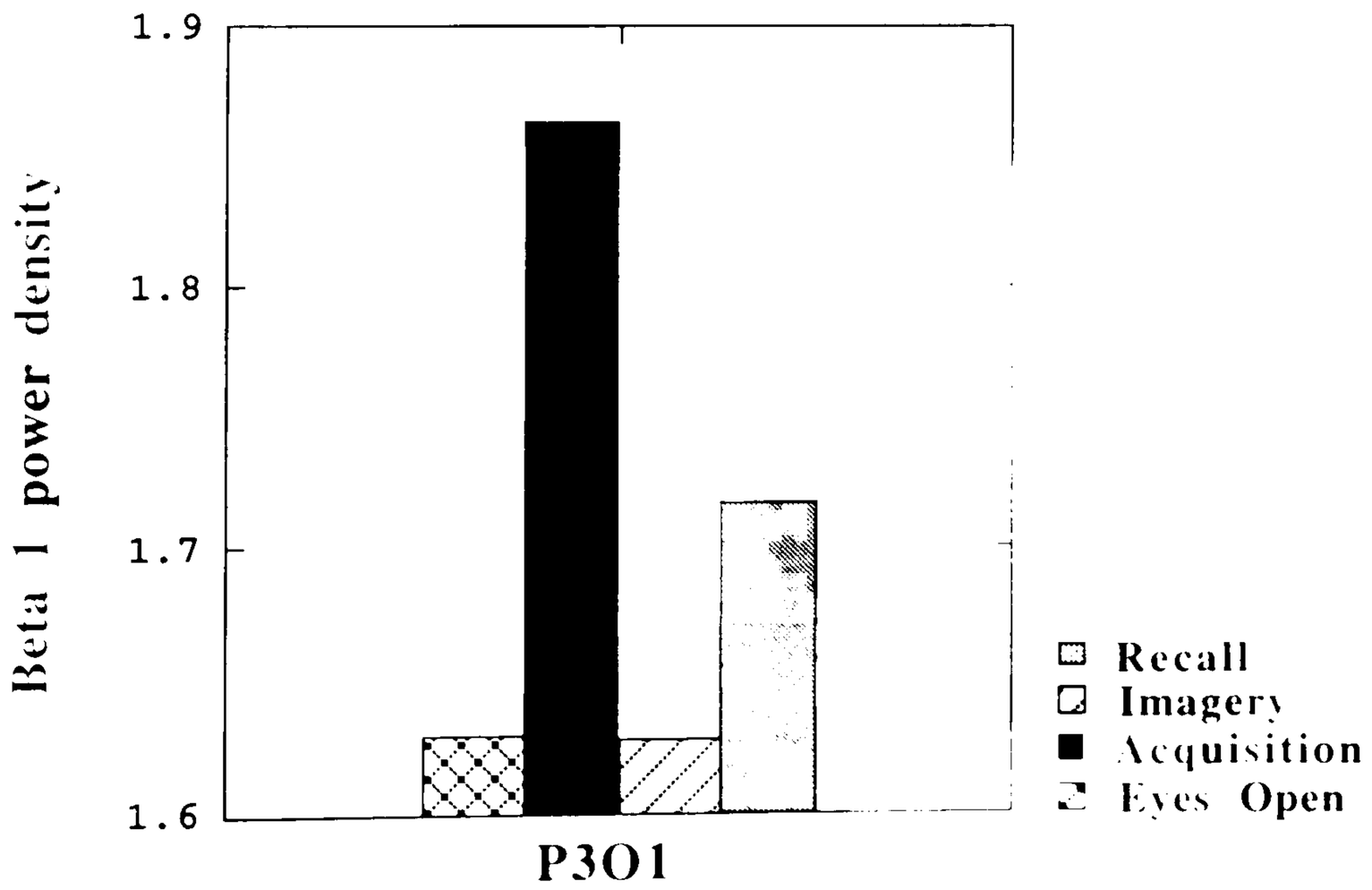
It is clear that there is a relationship between imagery ability and baseline EEG: as MRT performance improves, there is a decrease in power density. This suggests that those subjects who are good at such tasks have higher tonic activity during a resting baseline than those subjects who are poor at such tasks. The distribution of MRT scores is

positively skewed indicating that most subjects demonstrated relatively good ability on the MRT, so it is possible that the absence of any differences in power density between EO and MI is due to this high baseline activity.

Beta 1

The means and standard deviations of power density at each electrode in the beta 1 frequency band during each experimental condition are presented in Appendix A Table A8.2. The level of power density in beta 1 at the pre-frontal and parieto-occipital sites is almost identical during each of the four conditions. At the occipital and parieto-occipital sites, however, the levels of beta 1 are highest during those conditions which involve actual movement (particularly during ACQ) and are lowest during EO. This is seen clearly in Figure 8.10 which shows power density over the left parieto-occipital area during these conditions.

Figure 8.10 Beta 1 power density during each condition recorded over left parieto-occipital cortex

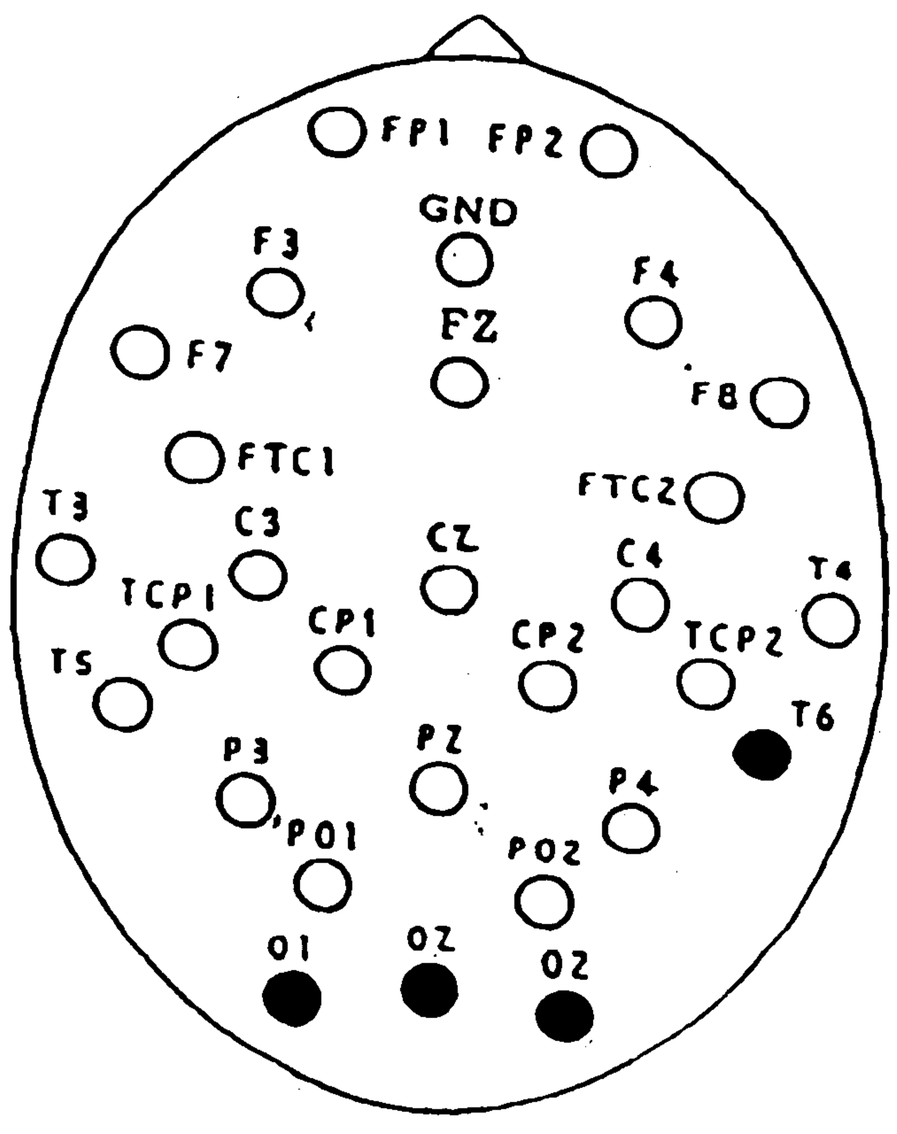


MANOVA indicated a significant effect of experimental condition [F (3, 19) = 33.54, p < 0.0005]. Repeated measures ANOVAs were performed on data recorded at each electrode during each of the four conditions. Significant effects were found at a number of sites, the details of which are summarised in Table 8.8. Those electrodes which show significant differences are shown in Figure 8.11

Table 8.8 Electrodes at which main condition effects were observed in beta 1

Electrode	d.f.	F-ratio	p
T6	3,63	4.78	0.01
O1	3,63	6.66	0.0008
Oz	3,63	8.87	0.0007
O2	3,63	6.61	0.002
P3O1	3,63	3.99	0.017
P4O2	3,63	5.77	0.004

Figure 8.11 Figure showing location of main condition effects in beta 1



A summary of the post hoc analysis is presented in Table 8.9

Table 8.9a Electrodes demonstrating a change in beta 1 from the eyes open baseline to the acquisition (learning) condition

Electrode	Condition	p (Tukey)
T6	EO* - ACQ	0.0001
O1	EO* - ACQ	0.001
Oz	EO* - ACQ	0.0001
O2	EO* - ACQ	0.0003
P3O1	EO* - ACQ	0.01
P4O2	EO* - ACQ	0.001

Table 8.9b Electrodes demonstrating a change in beta 1 from the imagery condition to the acquisition (learning) condition

Electrode	Condition	p (Tukey)
T6	MI* - ACQ	0.001
O1	MI* - ACQ	0.005
Oz	MI* - ACQ	0.017
P3O1	MI* - ACQ	0.021

Table 8.9c Electrodes demonstrating a change in beta 1 from the eyes open baseline to the recall condition

Electrode	Condition	p (Tukey)
T6	EO* - REC	0.0001
Oz	EO* - REC	0.017
O2	EO* - REC	0.03

* indicates lower power density ($\mu V^2/Hz$) during that condition

EO = Eyes Open Condition

ACQ = Learning Condition

MI = Mental Imagery Condition

REC = Recall Condition

In summary, Table 8.9 shows that there are significant differences between power density recorded during ACQ and REC compared to the EO baseline at a number of sites. It also

shows that there are differences the power density recorded during ACQ and MI. In each case there was higher power density in ACQ and REC. There were no differences between ACQ and REC or between EO and MI.

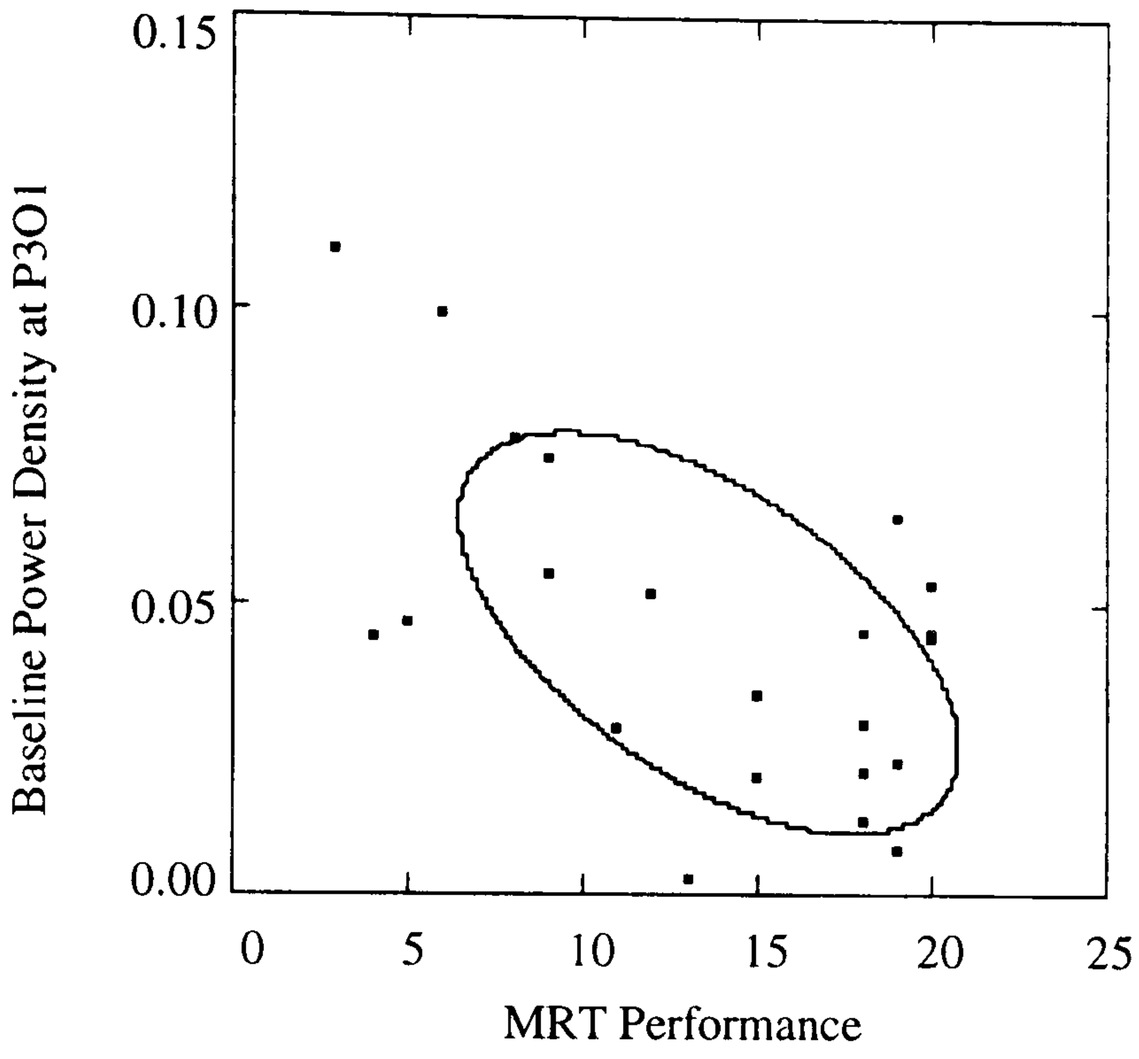
Following the regression procedures it was found that MRT performance consistently predicted a change in EEG from EO to MI. A summary of the results from the regression analyses is presented in Table 8.10

Table 8.10 Summary of Multiple Regression analyses showing that MRT performance predicts changes in EEG from the Eyes Open to the Imagery condition in beta 1.

	Coefficient	t	p	Spr (%)
P3	0.0016	3.38	0.004	31.6
O1	0.0022	4.15	0.001	40.6
P3O1	0.0019	4.91	0.0001	49.5

As in alpha there is a positive relationship between MRT performance and the change in EEG from EO to MI, implying that as MRT performance improves the difference between EEG recorded during these two conditions gets larger. Pearson correlations were performed between the MRT data and the EEG recorded during each condition at the sites outlined in Table 8.10: significant relationships being found at Oz ($r = -0.52$, $p = 0.01$) and P3O1 ($r = -0.57$, p ,0.005). Figure 8.12 provides an example of this relationship between activity at P3O1 and MRT performance.

Figure 8.12 The relationship between MRT performance and Power Density recorded at left Parieto-Occipital areas during the Eyes Open condition

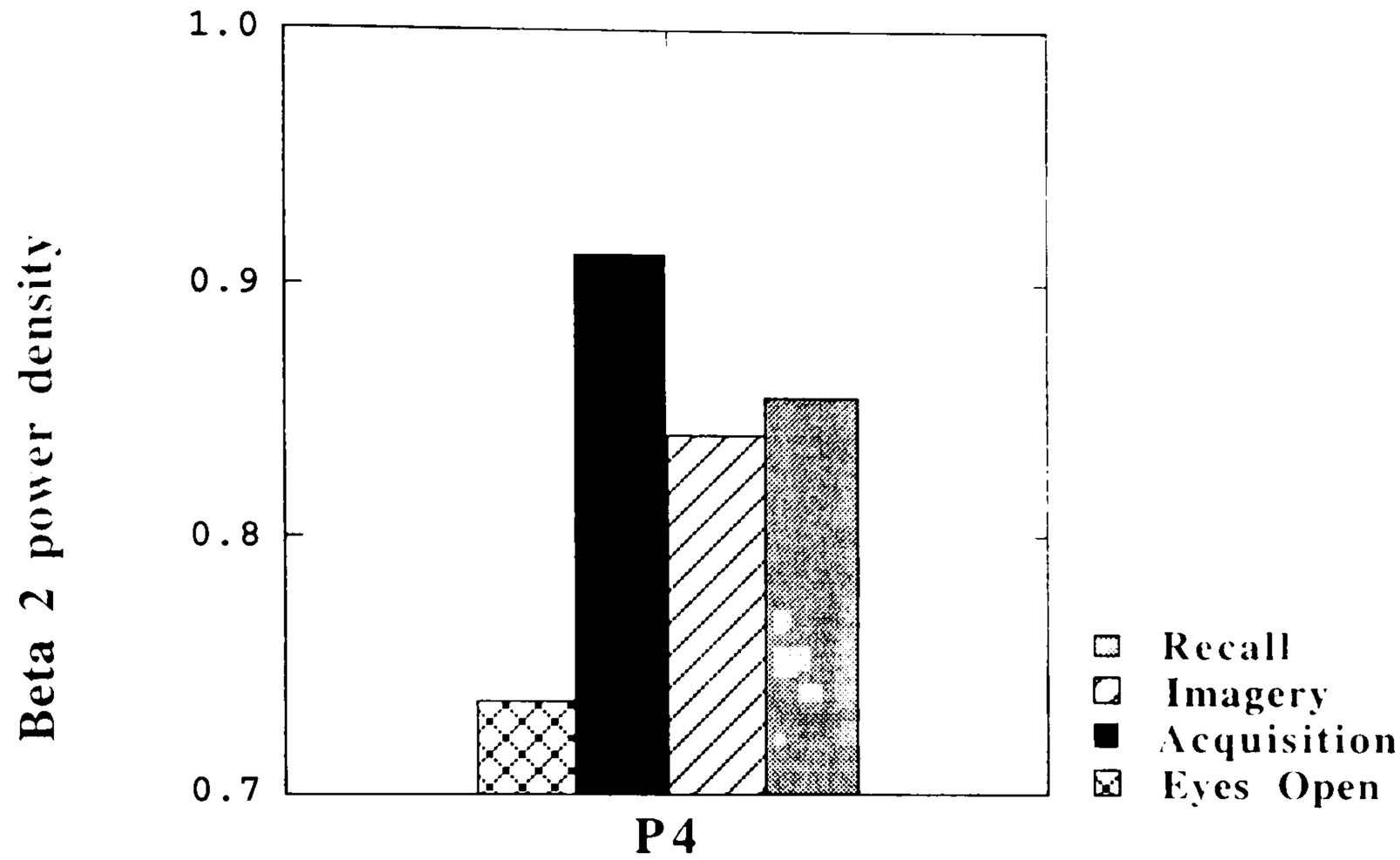


There were no significant relationships between MRT performance and EEG activity recorded during the imagery condition.

Beta 2

The means and standard deviations of power density at each electrode in the beta 2 frequency band during each of the four conditions are presented in Appendix A Table A8.3. As in beta 1 there appears to be very little difference in power density between the different conditions at frontal sites. At the parietal, occipital and parieto-occipital sites, however, levels of beta 2 are highest in those conditions that involved actual movement and lowest in the eyes open condition. This is illustrated in Figure 8.13 which shows power density levels of beta 2 recorded over the right parietal cortex.

Figure 8.13 Beta 2 power density during each condition recorded over right parietal cortex

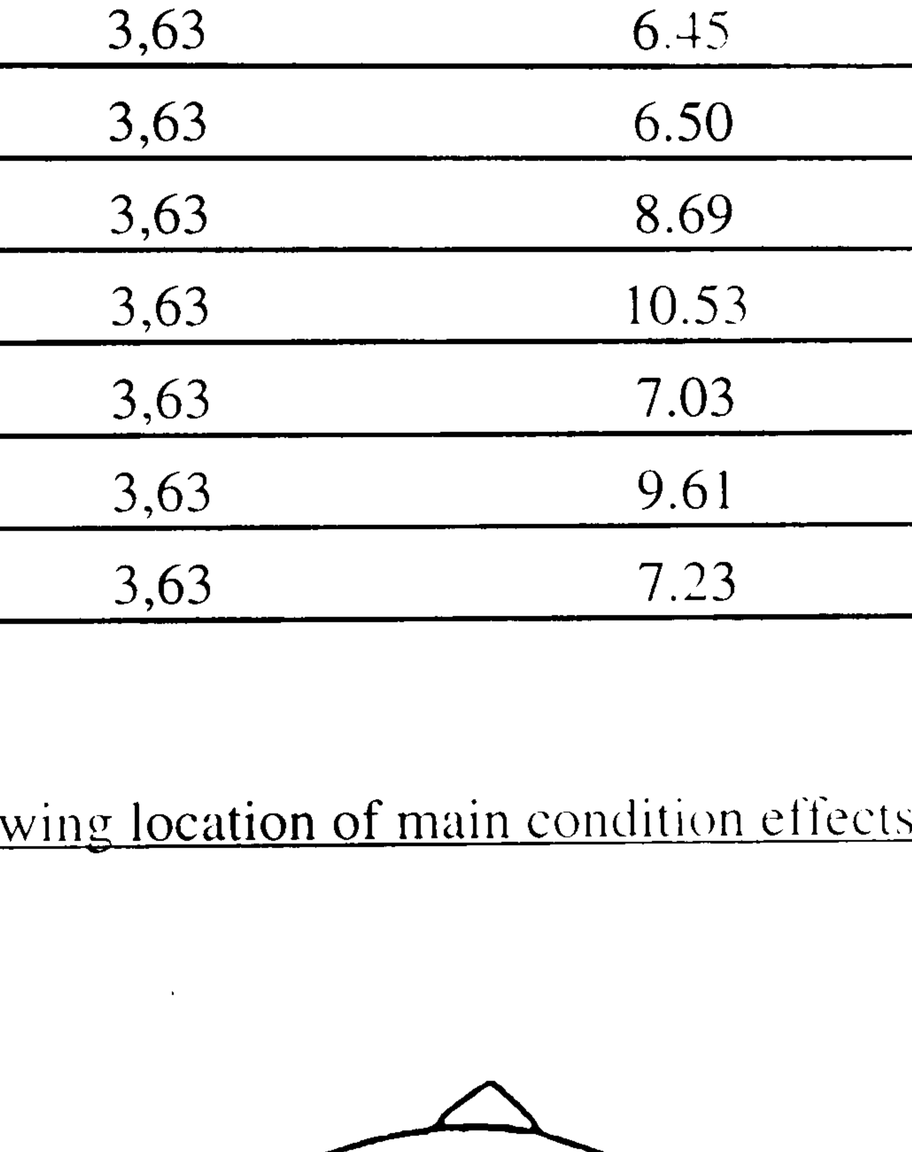


MANOVA indicated a significant effect of experimental condition [F (3, 18) = 13.46, p < 0.0005]. Repeated measures ANOVAs were performed on data recorded at each electrode during each type of condition. Significant effects were found at a number of sites, the details of which are summarised in Table 8.11. Those electrodes which show significant differences are shown in Figure 8.14.

Table 8.11 Electrodes at which main condition effects were observed in beta 2

Electrode	d.f.	F-ratio	p
T5	3,63	6.54	0.002
P3	3,63	11.10	0.00001
Pz	3,63	0.04	0.0002
P4	3,63	6.45	0.003
T6	3,63	6.50	0.003
O1	3,63	8.69	0.0002
Oz	3,63	10.53	0.00001
O2	3,63	7.03	0.0004
P3O1	3,63	9.61	0.00008
P4O2	3,63	7.23	0.002

Figure 8.14 Figure showing location of main condition effects in beta 2



A summary of the post hoc analysis is presented in Table 8.12

Table 8.12a Electrodes demonstrating a change in beta 2 from the eyes open baseline to the acquisition (learning) condition

Electrode	Condition	p (Tukey)
T5	EO* - ACQ	0.008
P3	EO* - ACQ	0.001
Pz	EO* - ACQ	0.0001
P4	EO* - ACQ	0.0003
O1	EO* - ACQ	0.0001
T6	EO* - ACQ	0.003
Oz	EO* - ACQ	0.0001
P3O1	EO* - ACQ	0.0001
P4O2	EO* - ACQ	0.0001

Table 8.12b Electrodes demonstrating a change in beta 1 from the eyes open baseline to the recall condition

Electrode	Condition	p (Tukey)
P3	EO* - REC	0.007
Pz	EO* - REC	0.02
P4	EO* - REC	0.017
T6	EO* - REC	0.014
Oz	EO* - REC	0.007
P3O1	EO* - REC	0.0001
P4O2	EO* - REC	0.02

Table 8.12c Electrodes demonstrating a change in beta 1 from the imagery condition to the acquisition (learning) condition

Electrode	Condition	p (Tukey)
P3	MI* - ACQ	0.0005
O1	MI* - ACQ	0.008
Oz	MI* - ACQ	0.002
P3O1	MI* - ACQ	0.01

* indicates lower power density ($\mu V^2/Hz$) during that condition

In summary Table 8.12 shows that power density is higher during ACQ and REC compared to the EO baseline and is also higher during ACQ compared to MI. There were no differences in power density between EO and MI or between ACQ and REC.

Regression procedures again showed that MRT performance consistently predicted the change in EEG from EO to the MI. A summary of the results from the regression analyses in beta 2 is presented in Table 8.13

Table 8.13

Summary of Multiple Regression analyses showing that MRT performance predicts changes in EEG from the Eyes Open baseline to the Imagery condition in beta 2.

	Coefficient	t	p	Spr (%)
P3	0.002	3.85	0.002	39.4
Pz	0.001	3.47	0.003	25.4
P3O1	0.002	3.61	0.003	31.3

Again, it can be seen that there are very significant positive relationships between EEG recorded during EO and MRT performance. Pearson correlations were performed between the MRT data and the EEG recorded during each experimental condition at the sites outlined in Table 8.13: P3 ($r = -0.55$, $p < 0.007$); Pz ($r = -0.47$, $p < 0.03$) and P3O1 ($r = -0.56$, $p < 0.006$).

The relationship between the different frequency bands

Power density was greater in the beta bands (particularly beta 2) during those experimental conditions that involved actual movement, which could have been caused by muscle contamination. One approach to this problem is to examine the relationship

between the frequency bands at the same electrode sites during the same condition; if an inverse relationship between the alpha and beta bands is observed during ACQ and REC but not during EO and MI, then one could suggest that the increase in beta power is due to muscle. If no such relationship is found then one might argue that these changes in the beta frequencies are not a result of muscle contamination but are characteristic of task related changes in these frequency bands. A series of correlations was calculated on the data recorded during all four experimental conditions some of which are presented in Table 8.14. The full set of results are presented in Appendix A Tables A8.7 - A8.10

Table 8.14 Pearson correlations between frequency bands at pre-frontal electrodes during acquisition and recall

		Acquisition			Recall		
		alpha	beta 1	beta 2	alpha	beta 1	beta 2
F7	alpha	1.00			1.00		
	beta 1	0.509**	1.00		0.562**	1.00	
	beta 2	0.160	0.851***	1.00	0.259	0.846***	1.00
F3	alpha	1.000			1.00		
	beta 1	0.751***	1.00		0.736***	1.00	
	beta 2	0.403	0.815***	1.00	0.593**	0.897***	1.00
Fz	alpha	1.00			1.00		
	beta 1	0.823***	1.00		0.803***	1.00	
	beta 2	0.576**	0.859***	1.00	0.591**	0.862***	1.00
F4	alpha	1.00			1.00		
	beta 1	0.651***	1.00		0.756***	1.00	
	beta 2	0.384	0.881***	1.00	0.502	0.868***	1.00
F8	alpha	1.00			1.00		
	beta 1	0.364	1.00		0.561**	1.00	
	beta 2	0.168	0.917***	1.00	0.262	0.859***	1.00

* $p < 0.05$

** $p < 0.01$

*** $p < 0.001$

Table 8.14 demonstrates that during overt movement there are positive correlations between alpha and beta 1 and between beta 1 and beta 2, though there is no evidence of any relationship between alpha and beta 2. More importantly, there is no evidence of any negative relationship between alpha and the two beta bands suggesting that the increase in power density during ACQ and REC was not due to muscle activity.

8.1.4 Discussion

In experiment 3 there were a number of predictions:

Behavioural Predictions

1. Interpolated activity consisting of either the actual production or the imagination of a movement half the length of previously learned movement was expected to result in the underestimation of the criterion position/distance of the movement. A bias in recall was not expected following a control task during which subjects counted backwards in threes subvocally. This effect would provide strong evidence of the use of movement imagery and its effect on STMM. These hypotheses were not confirmed; subjects overestimated the criterion distance following physical and mental practice. No significant differences were found between the different sessions and so no great confidence can be placed on the assumption that subjects were employing imagery.

2. It was predicted that there would be lower variability in recall following the *imagination* of a movement compared to the *actual production* of a movement different in extent to the criterion movement. This prediction was not confirmed by the data; although variability in the overt movement session was greater than in the imagery and control sessions, the differences between the means were not significant. Objective evidence of the use of movement imagery was, therefore, weak.

3. It was expected that MRT performance would demonstrate a stronger relationship than the VMIQ and MIQ to performance on the linear positioning task. It was also expected that the MIQ would exhibit a stronger relationship to performance than the VMIQ. These hypotheses were not supported by the data. None of the measures predicted the mean constant error of recall following the movement imagery condition.

4. It was predicted that if experience at making particular movements does not affect the rating of movement imagery, then there should be a relationship between the VMIQ and MIQ. A final prediction was that MRT performance would not be related to scores on the two questionnaires. These hypotheses were supported by the data; the two questionnaires show a strong correlation with each another, supporting previous findings (cf. Kilhlstrom, *et al.*, 1991) but were not related to MRT performance, findings that are consistent with data recorded during experiments 1 and 2.

Psychophysiological Predictions

1. It was expected that there would be an decrease in power density (increase in cortical activation) over the pre-frontal and parieto-occipital regions during overt and imaginary movement compared to an eyes open baseline, reflecting the planning of movement and the visuo-spatial nature of the underlying representations of the evoked image.

These predictions were not supported; there were no differences in the expected direction between EEG activity recorded during the eyes open baseline and mental imagery conditions at any of the electrodes sites examined. A difference was found over central occipital areas but power density was lower during the EO baseline.

2. Given the hypothesised functional equivalence of overt and imaginary movement it was also expected that there would be comparable levels of EEG power recorded at the pre-frontal cortex during actual and imagined movement.

This prediction was not supported by these data; highly significant differences were found between those conditions involving actual movement compared to the imagery condition. In alpha, power density was consistently lower during acquisition than in the imagery condition. In beta 1 and beta 2 there were no significant differences between any

of the conditions over pre-frontal cortex, so strictly speaking comparable levels of power density were found in the movement and imagery conditions. However, the fact that no differences were observed between these conditions and the baseline rules out any suggestion that the level of activity reflect similar processes.

3. A final prediction was that individual differences in imagery ability would predict changes in EEG activity from a baseline to an imagery condition, i.e. as imagery ability increased the difference in power density between the baseline and imagery conditions was expected to increase. In particular it was anticipated that this relationship would be based on objective performance (MRT) rather than on subjective assessment (VMIQ and MIQ).

This prediction was partially supported by these data; regression and correlation procedures showed consistently that the only measure related to EEG activity was MRT performance. As MRT performance increased, the difference between the baseline and imagery conditions did increase but was due to the greater power density in the imagery condition. Beyer, *et al.* (1990) and Marks and Isaac (1995) reported an increase in power during movement imagery and so this finding may be interpreted as supporting their results. However, the failure to observe any significant differences between the conditions does not allow any conclusion to be made on this point.

An alternative interpretation of this finding is that subjects who are good at MRT have lower power density (greater cortical activation) over the occipital cortex during EO. This might account for the failure to observe any differences between EO and MI; a high level of activation during EO may not allow any room for an effect to occur, assuming that power density decreases during cognitive activity. Correlations showed that as MRT performance increased, the level of power density decreased over occipital cortex during the baseline. One possible explanation of this finding is that baseline power in these subjects was too low for an effect to occur, but it is more likely that these results reflect a

combination of the low cognitive load produced by the task and the low baseline power of these subjects.

In summary, the behavioural data provide no evidence of functional equivalence between imagery and overt movement; interpolated activity did not have the expected effect on the recall of movement information. Furthermore, no evidence of functional equivalence was found in the EEG; no decrease in power was observed between the baseline and imagery condition and actual movement resulted in a highly significant decrease in power density compared to movement imagery.

With regard to individual differences in imagery ability, none of the measures used to assess imagery ability predicted performance on the linear positioning task. MRT did predict task related changes in EEG but these changes were in the opposite direction to those predicted. A suprising observation was that as MRT performance increased alpha power density over occipital cortex decreased, i.e. subjects who perform well on this task are characterised by a high level of baseline tonic EEG. Given that this task is argued to be spatial rather than motoric (Johnson, 1982), the finding that MRT did not predict performance is rather suprising. It is possible that the cognitive load of the task was too low and made few demands on spatial representations. The (insignificant) increase in power density during the imagery condition compared to the baseline would support this conclusion. It is also possible that different spatial representations are active in these two tasks: as Logie (1994) points out, the term 'spatial' is not very well defined and is used to describe cognitive processes in a wide range of experimental paradigms. It could be then, that movement imagery with a high spatial component involves different information than that used in imaginary transformations (cf. Smyth *et al.*, 1988).

8.2 Experiment 4

8.2.1 Introduction

During experiment 3 subjects had to imagine themselves making a simple movement which is considered by many to result in subjects using kinaesthetic imagery (Mahoney & Avener, 1977). It was argued that the adoption of a 'visual internal' perspective would involve visuo-spatial as well as motoric representations. Even if instructions emphasise the kinaesthetic element of the task there is always the possibility that subjects adopt a 'visual internal' perspective because of the visual feedback available during the experiment.

In experiment 4 an attempt was made to ensure that subjects generated kinaesthetic rather than visual images. Subjects were blindfold as it was reasoned that if no visual cues were available, they would have to rely on kinaesthetic information to generate images. Although it has been shown that kinaesthetic information decays more quickly than visual information, it nonetheless can be maintained in memory provided some form of rehearsal is available (Smyth, 1984). Indeed interpolated movement different in extent to a criterion movement produce the same effects when there are no visual cues (Patrick, 1971; Stelmach & Walsh, 1973). On the basis of these studies it was decided to repeat the procedure of the previous experiment and remove all visual feedback. If imagery of movement interfered in the expected manner and changes in the EEG were over cortical areas thought to be involved in the processing of kinaesthetic/proprioceptive information, then one might argue that the instructions to imagine the sensations of making the movement would result in imagery that involves kinaesthetic and motoric representations.

The predictions were similar to those outlined in the previous experiment:

Behavioural Predictions

1. Interpolated movement half the length of a criterion movement would result in a bias in recall in the direction of the interpolated movement.

2. Due to the decay of kinaesthetic information in the absence of rehearsal it was expected that variability would be greatest following the control task. It was also expected that there would be greater variability in recall following actual movement compared to imaginary movement.

3. Given the results of experiment 3, no relationship was expected between the different measures of imagery ability and performance on the linear positioning task. The VMIQ and MIQ scores were expected to correlate with each other but no relationship was expected between these measures and MRT performance.

Psychophysiological Predictions

1. Given the hypothesised role of the pre-frontal cortex in the formation of action plans it was predicted that in comparison to an eyes closed baseline, imagery of movement would result in lower power density over pre-frontal cortex. A decrease in activity was also expected over parietal cortex reflecting the activation of kinaesthetic representations.

2. The pre-frontal cortex is thought to be involved both in the formation of action plans and in imagery of movement, so it was predicted that there would be comparable levels of EEG over the pre-frontal areas of the cortex during *actual* movement and *imagery* of movement.

3. It was also predicted that individual difference measures would be related to these changes in the EEG.

8.2.2 Method

Subjects

18 of the 24 subjects (12 male, 6 female) aged 21 - 34 were selected from the research staff at the Centre of Human Sciences, Defence Research Agency, Farnborough.

Apparatus and Materials

Subjects completed the Vandenberg and Kuse (1978) MRT, the Vividness of Movement Imagery Questionnaire (VMIQ) (Isaac *et al.*, 1986) and a modified version of the Movement Imagery Questionnaire (MIQ) (Hall *et al.*, 1985).

The experimental apparatus for the linear positioning task was identical to that used in experiment 3.

Procedure

The design and procedure was identical to that used in the previous experiment, except that subjects had no visual feedback from the environment and were blindfold in all conditions. In accordance with these conditions, the baseline was 'eyes closed'.

Apparatus and EEG Recording

The EEG equipment, recording parameters and artifact removal procedures are described in chapter 5. A minimum of 10 artifact free epochs (20 secs) from each subject in each

condition was used in the analysis. The mean duration of artifact free data across all subjects was 35 epochs (70 secs) for the eyes closed baseline, 32 epochs (64 secs) for the acquisition trials, 22 epochs (44 secs) for the movement imagery condition and 29 epochs (58 secs) for the recall conditions.

Data from five anterior electrodes (F3, Fz, F4, F7 and F8) and eight posterior electrodes (T5, P3, Pz, P4, T6, O1, Oz and O2) were downloaded for more detailed analysis. Additional occipito-parietal variables (P3O1, P4O2) were derived by calculating the mean power density at these sites [e.g. P3O1 = (P3+O1) /2]. Output from the imager provided spectral power values (in μV^2) in bins of 0.5 hertz and from these power density values ($\mu V^2/Hz$) were calculated in the alpha, beta 1 and beta 2 frequency bands (see Chapter 5). The data in all 3 frequency bands were found to be skewed and were log transformed prior to further analysis to normalise their distributions.

8.2.3 Results

Data analysis procedures were identical to those outlined in experiment 3. Analysis consisted of the calculation of the mean constant and mean variable error which were subsequently subjected to ANOVA. Analysis of EEG data consisted of MANOVAs, ANOVA followed by multiple regression and correlation procedures.

8.2.3.1 Behavioural data

8.2.3.1a Constant error

A summary of the mean and standard error of CE are shown in Table 8.15 which shows that the production of a movement half the length of a previously learned movement

produced a bias in recall in the expected direction. That is, subjects underestimated the length of the criterion movement. The expected bias due to movement imagery was not observed. Contrary to the previous experiment interpolated activity in the control condition did not produce a negative bias in recall. The effects of the different types of interpolated activity on constant error is shown in Figure 8.15.

Figure 8.15 Mean Constant Error of recall of the criterion movements following the different types of interpolated activities

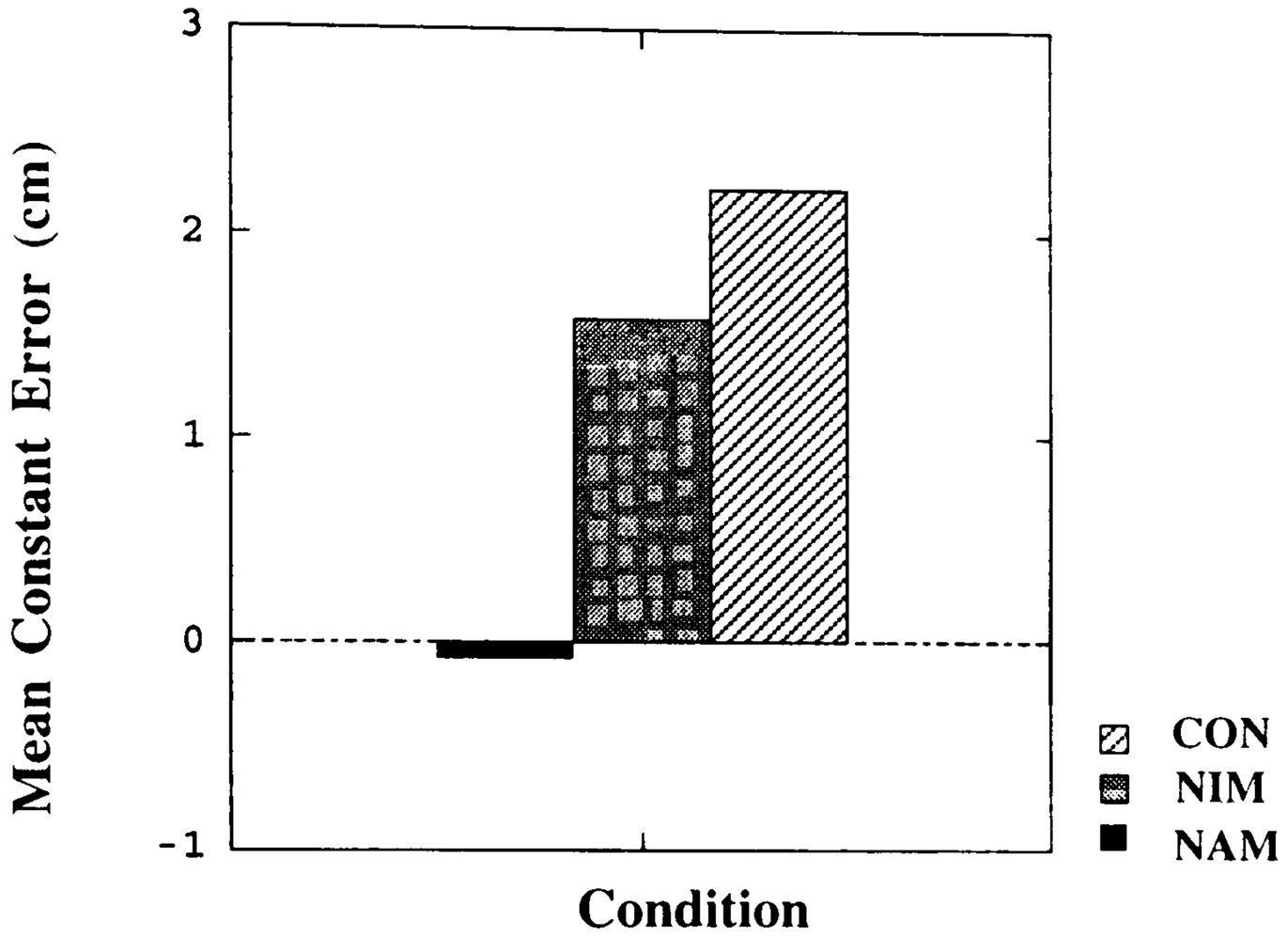


Table 8.15 Summary of mean (X) and standard error (SE) for constant error (CE) in each experimental condition of Experiment 4.

		NAM	NIM	CON
CE	(X)	-0.076	1.581	2.231
	(SE)	1.461	1.808	1.209

NAM = Novel Imaginary Movement

NIM = Novel Actual Movement

CON = Control

A one way ANOVA using constant error as the dependent variable showed a non significant effect for type of interpolated activity, $F(2,42) = 2.303$, $p > 0.05$.

8.2.3.1b Variable error

A summary of the mean and standard error of VE are shown in Table 8.16 which shows that there is very little difference in the mean VE of the different conditions. See Figure 8.16.

Figure 8.16 Mean Variable Error of recall of the criterion movements following the different types of interpolated activities

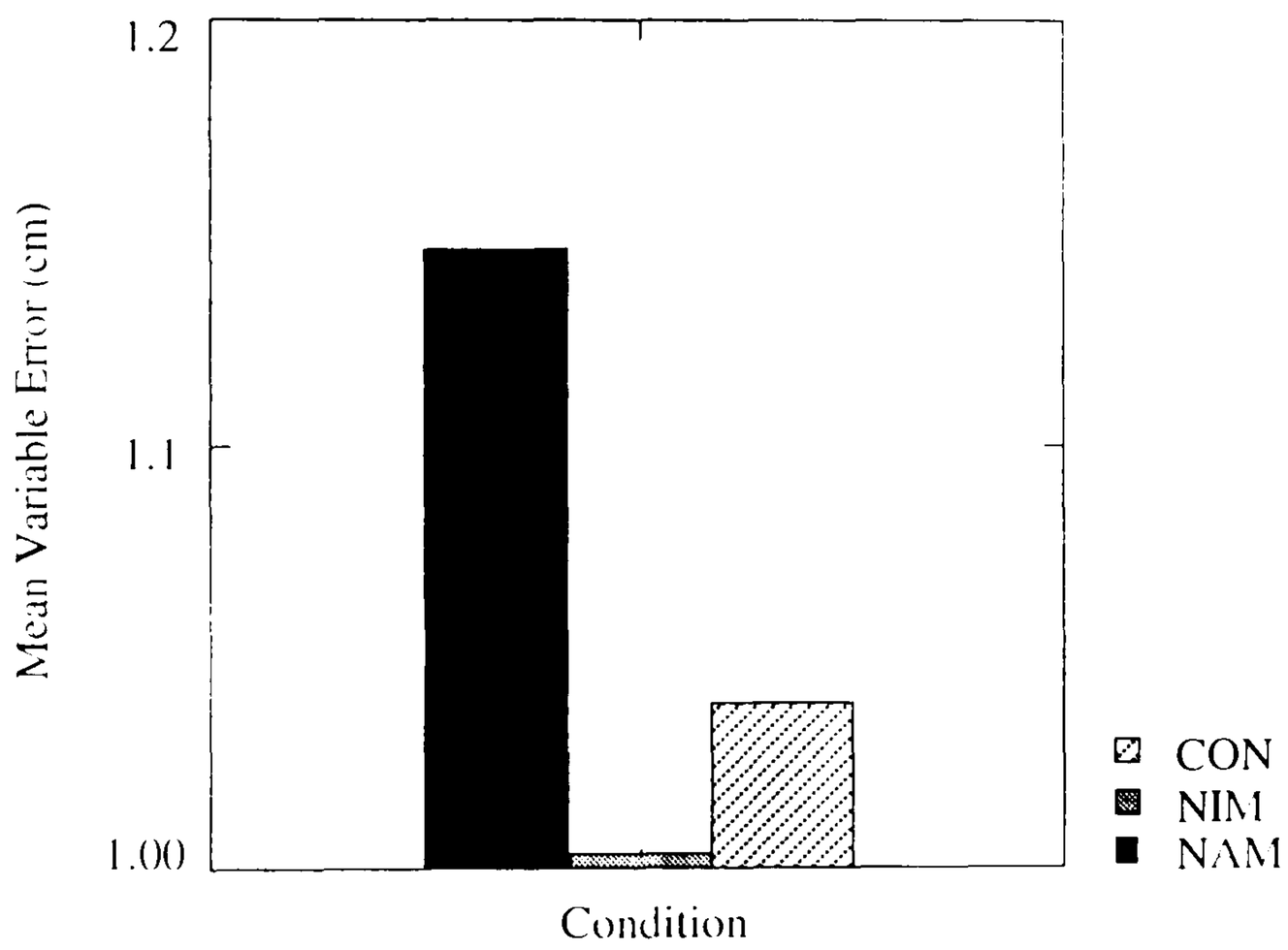


Table 8.16 Summary of mean (X) and standard error (SE) for variable error (VE)

		NAM	NIM	CON
VE	(X)	1.147	1.004	1.038
	(SE)	0.194	0.186	0.130

NAM = Novel Actual Movement
NIM = Novel Imaginary Movement
CON = Control

A one way ANOVA using constant error as the dependent variable showed a non significant effect for type of interpolated activity, $F(2,42) = 0.233$, $p > 0.05$.

8.2.3.1c Individual Differences

The means and standard deviations of the VMIQ, the MIQ and the MRT in experiment 4 are presented in Table 8.17

Table 8.17 Summary of means and standard deviations of the VMIQ, MIQ and MRT.

	VMIQ__T	VMIQ_K	VMIQ_V	MIQ_T	MIQ_K	MIQ_V	MRT
Mean	128.667	66.500	62.167	35.833	18.389	17.444	14.278
SD	35.314	18.912	19.172	14.127	7.830	7.023	3.816

T = Total
K= kinaesthetic Imagery Score
V = Visual Imagery Score

As in experiment 3, subjects classified their movement images as moderately vivid to very vivid. They also performed well in the MRT task. In order to test whether any of these measures predicted recall of the criterion movement following novel imaginary movement (NIM), a multiple regression analysis was performed using the total scores on both questionnaires and MRT performance as independent variables and mean constant error from the imagery session as the dependent variable. None of these measures significantly predicted constant error scores on the linear positioning task, $F(3,14) = 2.068$, $p > 0.05$. Multiple regression analysis was also performed using mean variable error as the dependent variable; none of the measures predicted variable error scores, $F(3,14) = 1.032$, $p > 0.05$.

A series of correlations were performed between the VMIQ, MIQ and MRT. No relationship was found between performance on the MRT and self report imagery ability according to the VMIQ ($r = -0.370$, $p > 0.05$) or the MIQ ($r = 0.252$, $p > 0.05$). A non significant relationship was found between the VMIQ and the MIQ, ($r = 0.176$, $p > 0.05$).

Correlations performed between the visual imagery and kinaesthetic components of each individual questionnaire showed highly significant relationships: VMIQ ($r = 0.720$, $p = 0.001$), and MIQ ($r = 0.809$, $p = 0.0005$). No relationships were observed between the visual sub-scales of the VMIQ and the MIQ ($r = 0.141$, $p > 0.05$) or between the kinaesthetic components ($r = 0.10$, $p > 0.05$). No relationship was found between the kinaesthetic and visual components of the VMIQ and MIQ ($r = 0.44$, $p > 0.05$).

8.2.3.2 Psychophysiological data

Alpha

The means and standard deviations of power density at each electrode in the alpha frequency band recorded during each of the four experimental conditions are presented in Appendix A Table A8.4. There appears to be very little difference in alpha between the four conditions. MANOVA indicated a significant condition effect [$F(3, 13) = 59.15$, $p < 0.0005$] but repeated measures ANOVAs performed on data recorded at each electrode during each condition failed to show any significant effects at any of the electrode sites. Multivariate multiple regression procedures failed to produce any significant omnibus tests and so no further multiple regression or correlation tests were performed.

Beta 1

The means and standard deviations of power density at each electrode in the beta 1 frequency band during each experimental condition are presented in Appendix A, Table

A8.5. Power density in beta 1 was higher at posterior sites compared to that recorded over pre-frontal sites. At most of the pre-frontal sites the levels of beta 1 were lowest during acquisition (ACQ) and recall (REC) though a different picture emerged at posterior sites: levels of beta 1 at occipital and parieto-occipital sites were highest during these conditions. Power density recorded during each condition over anterior and posterior sites are illustrated in Figure 8.17 and 8.18.

Figure 8.17 Power density in beta 1 over anterior cortex (Fz) during each experimental condition

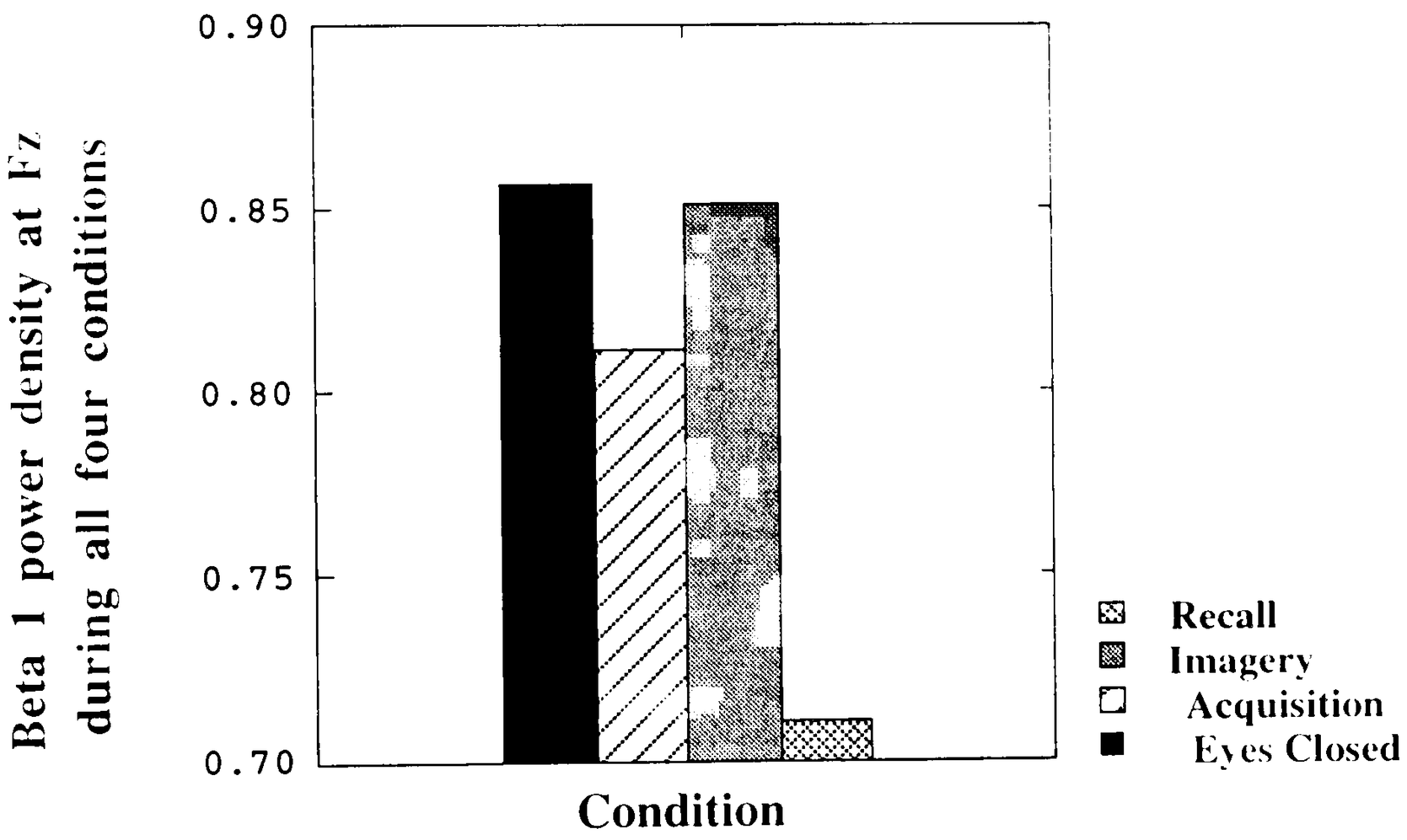
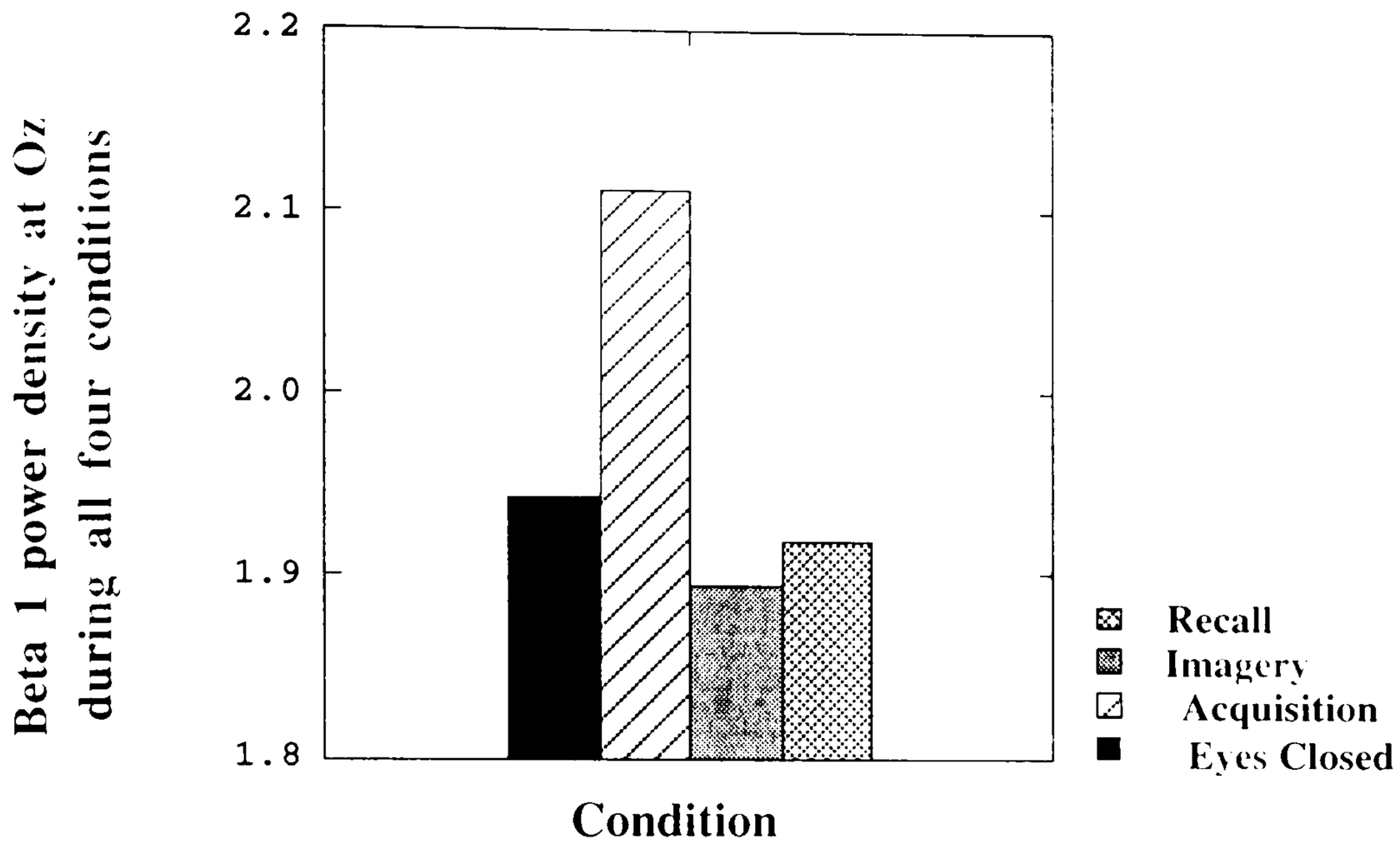


Figure 8.18 Power density in beta 1 over posterior cortex (Oz) during each experimental condition

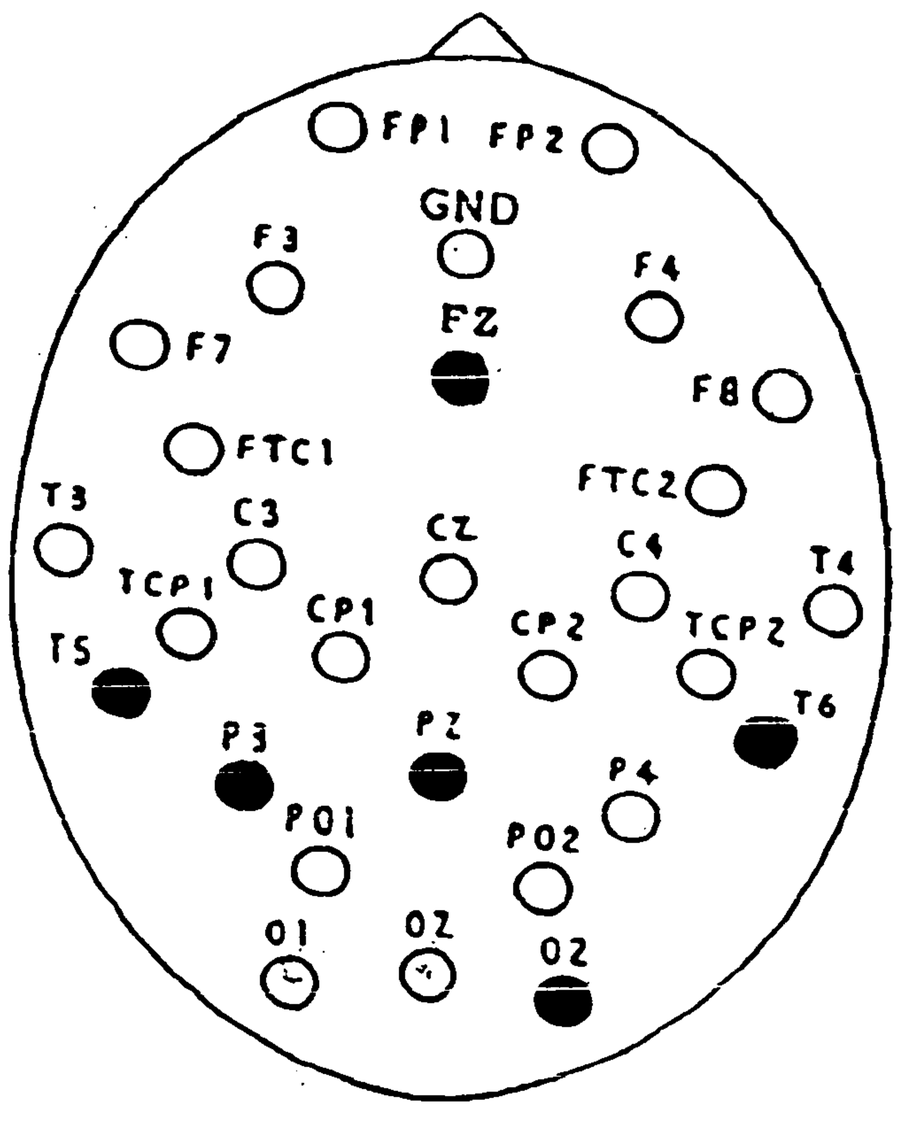


MANOVA indicated a significant condition effect [F (3, 13) = 30.184, $p < 0.0005$]. Repeated measures ANOVAs were performed on data recorded at each electrode during each type of condition. Significant effects were found at a number of sites, the details of which are summarised in Table 8.18. Those electrodes which show significant differences are shown in Figure 8.19.

Table 8.18 Electrodes at which main condition effects were observed in beta 1

Electrode	d.f.	F-ratio	p
Fz	3,51	11.13	0.001
T5	3,48	15.52	0.0003
P3	3,48	6.34	0.002
Pz	3,45	7.72	0.001
T6	3,51	29.29	0.0001
O2	3,48	3.4	0.04

Figure 8.19 Figure showing location of main condition effects in beta 1



A summary of the post hoc analysis is presented in Table 8.19

Table 8.19a Electrodes demonstrating a change in beta 1 from eyes closed baseline to the acquisition (learning) condition

Electrode	Condition	p (Tukey)
Pz	EC - ACQ*	0.01
O2	EC* - ACQ	0.02

Table 8.19b Electrodes demonstrating a change in beta 1 from eyes closed baseline to the recall condition

Electrode	Condition	p (Tukey)
Fz	EC - REC*	0.0002
P3	EC - REC*	0.0007
Pz	EC - REC*	0.0002
T6	EC* - REC	0.0001

Table 8.19c Electrodes demonstrating a change in beta 1 from eyes closed baseline to the imagery condition

Electrode	Condition	p (Tukey)
T5	MI - EC*	0.0003

Table 8.19d Electrodes demonstrating a change in beta 1 from the imagery condition to the acquisition (learning) condition

Electrode	Condition	p (Tukey)
T5	MI - ACQ*	0.0001

Table 8.19e Electrodes demonstrating a change in beta 1 from the imagery condition to the recall condition

Electrode	Condition	p (Tukey)
Fz	MI - REC*	0.0002
T5	MI - REC*	0.0001
P3	MI - REC*	0.026
T6	MI* - REC	0.0001

Table 8.19f Electrodes demonstrating a change in beta 1 from the **acquisition** condition to the recall condition

Electrode	Condition	p (Tukey)
Fz	ACQ -REC*	0.0002
T6	ACQ* -REC	0.0001

* indicates lower power density ($\mu V^2/Hz$) during that condition

EC = Eyes Closed Condition
ACQ = Learning Condition
MI = Mental Imagery Condition
REC = Recall Condition

In summary power density was found to be lower during ACQ and REC compared to EC and MI at all of the electrodes that demonstrated a change in activity. The only exceptions to this were at T6 and O2 where power density was higher during EC and MI . The only difference between the MI and EC was at T5 where power density was found to be lower in the EC baseline condition.

Multivariate multiple regression procedures failed to produce any significant omnibus tests and so none of the measures of imagery ability predicted these changes in EEG activity. As multivariate procedures did not produce any significant results, no further regression or correlation tests were performed.

Beta 2

The means and standard deviations of power density at each electrode in the beta 2 frequency band during each of the four conditions are presented in Appendix A, Table A8.6. As is the case in the other frequency bands power density is higher over posterior regions of the cortex. There is little difference in power density between the different conditions over pre-frontal cortex but there appears to be higher power density over

posterior electrodes during the acquisition condition compared to the other conditions. See Figures 8.20 and 8.21.

Figure 8.20 Power density in beta 2 over anterior cortex (Fz) during all four conditions of experiment 4

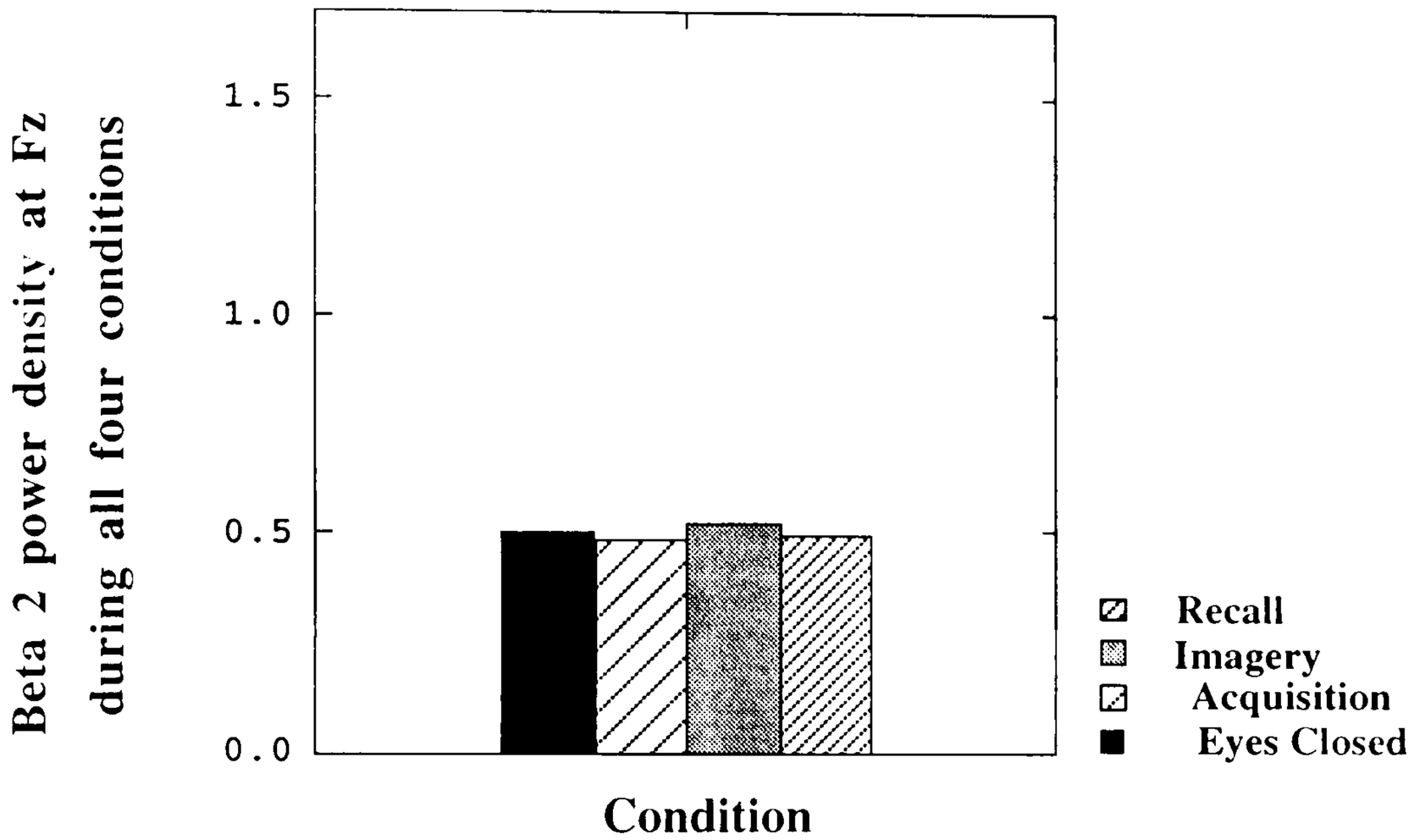
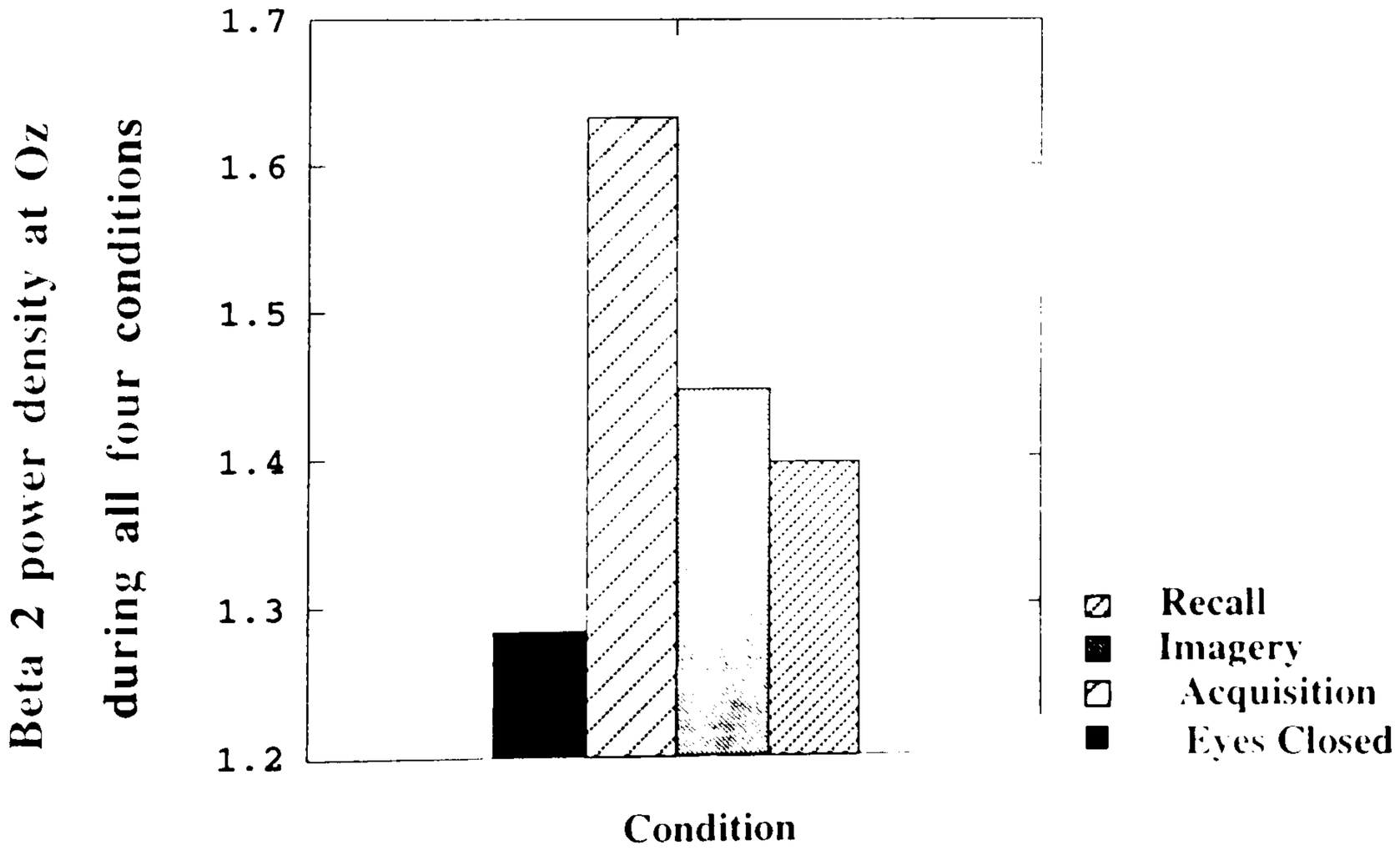


Figure 8.21 Power density in beta 1 over posterior cortex (Oz) during all four conditions of experiment 4



MANOVA indicated a significant condition effect [F (3. 13) = 9.205. p < 0.002]. Repeated measures ANOVAs showed significant effects at **OZ** [F (3,48) = 3.55. p < 0.04]; **O2** [F (3,48) = 6.53, p , 0.005] and **P4O2** [F (3,48) = 5.672. p < = 0.001]. A summary of the post hoc analysis is presented in Table 8.20.

Table 8.20a Electrodes demonstrating a change in beta 2 from eyes closed baseline to the Acquisition (learning) condition

Electrode	Condition	p (Tukey)
Oz	EC* - ACQ	0.005
O2	EC* - ACQ	0.005
P4O2	EC* - ACQ	0.001

Table 8.20b Electrode demonstrating a change in beta 2 from eyes closed baseline to the recall condition

Electrode	Condition	p (Tukey)
P4O2	EC* - REC	0.031

Table 8.20c Electrode demonstrating a change in beta 2 from eyes closed baseline to the imagery condition

Electrode	Condition	p (Tukey)
P4O2	EC* - MI	0.031

* indicates lower power density ($\mu V^2/Hz$) during that condition

EO = Eyes Open Condition

ACQ = Learning Condition

MI = Mental Imagery Condition

REC = Recall Condition

Multivariate multiple regression procedures failed to produce any significant omnibus tests, demonstrating that the different measures of imagery ability were not related to task related changes in EEG. No further multiple regression or correlation tests were performed.

8.2.4 Discussion

In experiment 4 a number of predictions were stated:

Behavioural Predictions

1. It was predicted that interpolated activity consisting of either the *actual production* or the *imagination* of a movement half the length of previously learned movement would lead to subjects underestimating the criterion position/distance of the movement. A bias in recall was not expected following a control task during which subjects counted backwards in threes subvocally.

This prediction was not supported by the data; no bias was found following imaginary movement. A bias following the overt movement was observed in the expected direction and although it was not sufficiently large to produce a significant effect it does demonstrate that the demands of this task were greater than in Experiment 3

2. Due to the expected decay of kinaesthetic information in the absence of rehearsal, it was expected that variability of recall would be greatest following the control task. It was also expected that variability of recall would greater following *actual* movement compared to imaginary movement.

These predictions was not confirmed, there being very little difference in the mean variable error of these three conditions.

3. It was further predicted that there would be a relationship between the different measures of imagery ability and performance on the linear positioning task.

This prediction was not supported by the data; measures of individual differences were not related to constant error scores following the interpolated imagery condition.

4. It was expected that the vividness ratings obtained from the VMIQ and MIQ would correlate with each other, though neither of these measures was expected to be correlated with MRT performance. These predictions were partially supported; no relationship was found either between the two questionnaires or between the MRT and the vividness questionnaires.

Psychophysiological Predictions

1. It was expected that there would be a decrease in power density (increase in activation) over the pre-frontal and parietal cortex during overt and imaginary movement reflecting the planning of movement and the spatial and kinaesthetic nature of the underlying representations of the evoked image.

The data did not support this prediction. In alpha, although MANOVA was found to be significant, no significant differences between any of the conditions were found at any of the electrodes examined following univariate procedures. The results of the univariate analyses are adjusted to take sphericity into account and this more rigorous test resulted in some tests being regarded as non-significant where they would otherwise be reported as significant. In beta 1 a difference was observed between the baseline and imagery conditions over the right temporal region, though power was higher in the baseline condition. In beta 2 although a difference was observed over the right parieto-occipital cortex there was higher power density during the imagery condition.

2. It was expected that there would be comparable levels of power density recorded during movement and imagery at electrodes situated over the pre-frontal cortex.

The data did not support this prediction; in beta 1 power density was significantly lower during the acquisition and recall condition compared to the imagery condition. In beta 2 power density was significantly higher during acquisition and recall.

3. It was also expected that changes in EEG from an EC baseline to an imagery condition would be predicted by MRT performance and the VMIQ and MIQ.

No significant relationships were found these measures and EEG data following the regression and correlation procedures outlined in Chapter 5.

8.3 General Discussion of Experiments 3 & 4

Perhaps the most surprising results of these two experiments is the failure to replicate the results reported by Johnson (1982) and so it necessary first to examine differences between the procedure used in the two studies in an attempt to explain these findings. The parallel recording of EEG imposed a number of restrictions on the experimental design and so a number of changes were made to the experiment described by Johnson (1982), the most important being that this study incorporated a repeated measures design whereas Johnson used a completely randomised design. The repeated measures design was chosen not only because it provides more powerful analysis but because it also requires fewer subjects; given the small number of subjects available and the time taken to prepare subjects for an EEG study this design was considered more appropriate.

It seems unlikely that the different experimental design accounts entirely for the failure to replicate Johnson's results. The biasing effect of an interpolated movement different in

extent to the criterion is well documented and Patrick (1971) also used a repeated measures design, so it is more likely that some changes to the procedure may be responsible for these results. In Johnson's experiments subjects performed 15 learning trials, engaged in interpolated activity for 40 seconds and then performed 10 recall trials whereas in this experiment subjects had 15 learning trials, engaged in 60 seconds of interpolated activity and had 15 recall trials. These alterations were made to ensure that sufficient EEG was recorded to provide a representative sample of cortical activity.

While these changes may have introduced additional sources of variability into the data it is suggested that potentially the most important difference in the procedure is the timing of the movements, both overt and imagined. In this study, subjects were not constrained in any of the conditions and their movements were self paced whereas in Johnson's experiments, overt and imaginary movements during the learning and interpolated condition were paced by two lights which flashed alternately with a two second interval between each light. In experiment 1 of Johnson's experiments, subjects learned movements of either 30 cm or 60 cm (i.e. they moved at either 15 cm/second or 30 cm/second) but during the interpolated tasks they made or imagined making movements that were either twice or half the length of the previously learned movement (i.e. 60 cm or 30 cm). Although it is not made explicit in the paper, the timing of the lights was presumably the same which means the velocity of these interpolated activities was different to that encoded during learning. This change may have a caused an alteration of the parameters stored in the representation of the goal plan and it is argued that this change which could have resulted in the observed interference.

The experiments reported here did not include an external pacing mechanism as it was reasoned that this device could introduce artifactual evoked potentials into the EEG data. Instead, overt and imaginary movements were self paced, which may have introduced greater variability in the velocity of the movements. The memory trace of this movement would, therefore, be weak compared to that laid down under fixed constraints. If force

and temporal information are represented in the planning of movement, then this has important consequences for the procedure used in these experiments as these parameters may not have been encoded in the representation of the movement during the acquisition condition. By the same token, this information may not have been encoded during imagery of a self paced movement. If this is the case then it is may not be so surprising that the interpolated activity did not cause the expected interference.

It is important to note that Johnson's second experiment was interpreted as showing that the interference was perceptual rather than motoric in nature as is suggested here. Interpolated activities included overt and imaginary movement with or without a secondary interference activity (watching an oscillating waveform - visual; squeezing a dynamometer - motor). The timing of the overt and imagined movements was again synchronised to an external cue and it was found that each of the interpolated tasks, with the exception of imagery with second-order visual interference, led to the expected bias in recall. These results were interpreted as showing that imagery for movement is perceptual rather than motoric in nature.

It is possible that the second-order visual task interfered not only with the perceptual (spatial) element of the goal plan but also interfered with the encoding of the force needed to effect the acceleration necessary to time the movements. Subjects had to attend to an oscillating waveform, an external timing mechanism and generate a movement image, yet the assumption of Johnson is that the waveform interferes only with the generation of movement imagery and not with the external cue. Presumably this could also have happened so that force was not encoded resulting in the lack of interference. Second order motor interference resulted in the expected bias in recall because it did not disrupt the encoding of force; constant pressure on a dynamometer is characterised by tonic rather than phasic activity (which is not the case in the visual interference task) so very little afferent information was being transmitted by the golgi tendon organs once the initial phasic response was over. A second order motor task which does involve phasic

contraction of the muscles would likely disrupt the encoding of force and produce the necessary interference.

The absence of any interference effects in the linear positioning tasks provides very little objective evidence that imagery was being used, and this has important implications for the EEG activity recorded during these experiments. In both experiments movement imagery did not result in the expected decrease in power density when compared to a baseline, suggesting that the demands of the task were low and by implication that an adequate representation of the movement image was not formed during the imagery condition. In both experiments the only significant differences between the baseline and imagery conditions were found at Oz: in experiment 3 alpha power density was lower during the eyes open baseline and in experiment 4 power density in beta 2 was lower during the eyes closed baseline. The difference between the two conditions was, therefore, in the opposite direction to that predicted and could be interpreted as showing that during movement imagery, EEG is enhanced rather than suppressed. Given the inconsistency of this finding across all three frequency bands, and reports that suppression does occur during movement imagery (Breitling et. al. 1985), such an interpretation is rejected and very little significance is attached to these isolated examples of changes in the EEG.

It is suggested that the absence of any changes in the EEG during movement imagery was due to the fact that representations of the movements were not formed in sufficient detail to allow a conscious examination of their contents. This is particularly the case in alpha: it was proposed in chapters 5 and 6 that alpha is an index of attentional processes both to external stimuli and internal processes. If an adequate representation of the movement was not formed it is unlikely that subjects were able to bring it to conscious awareness and attend to it during imagery, this being demonstrated particularly in experiment 4 where no differences in alpha were found between any of the experimental conditions. In experiment 3 less power density was observed during actual movement, but subjects had

visual feedback whereas during the same conditions of experiment 4 no visual feedback was available. The absence of any change between the baseline and imagery in experiment 3 and the complete absence of condition effects in alpha in experiment 4 is, therefore, likely to be a result of the very small amount of information available to subjects during encoding.

The majority of changes in the EEG in both experiments were in relation to overt movement though the direction of these changes varied according to the different frequency bands. In experiment 3 power density decreased in alpha during movement though it increased in the beta bands. These findings could be interpreted as reflecting muscle contamination in the faster frequencies but given the results of the correlational analysis this seems unlikely. Indeed, when higher levels of beta were observed this was primarily over posterior not over pre-frontal cortex, where muscle related artifact would be expected. Furthermore, in experiment 4 levels of beta 1 were actually lower during movement compared to the baseline both over the pre-frontal and right temporo-parietal cortex. These findings suggest that alpha and beta vary independently according to the experimental conditions e.g. whether subjects engage in some form of perceptuo-motor activity as opposed to non motoric cognitive activity.

It might also be suggested that EEG is insufficiently sensitive to answer questions about functional equivalence. Movement imagery is assumed to comprise distributed processing which is likely to result in very small changes in activity over many parts of the cortex, whereas changes in the EEG associated with overt movement, are comparatively large. Indeed, the observation from PET that the supplementary motor area is active during the imagination of a finger apposition task was derived not by subtracting imagery data from movement data but by subtraction from data recorded during a resting baseline (Roland ***et al.***, 1980).

The question still remains as to why no consistent differences were observed between the baseline and the imagery condition. In experiment 3 regression and correlation analysis showed resting EEG was related to MRT; subjects who performed well on the MRT task had lower levels of baseline alpha. A possible interpretation of this finding is that high cortical activity in the baseline precluded any observable changes associated with imagery. Although the failure to observe any changes in the EEG is probably related to the experimental procedure and the arguments presented above, these results have important implications for what is considered to be an adequate baseline in EEG studies.

As in previous experiments, no relationship was observed between objective and subjective measures of imagery ability. The observation that only MRT performance was related to EEG activity is important given the finding in experiment 3 that subjects classified as good or poor MRT imagers, had more focal cortical activation during an imagery task. Similar results were not observed when these same subjects were classified according to more subjective measures in the form of the VMIQ. This suggests that an objective measure of imagery like MRT is a more subtle index of individual differences in imagery ability than questionnaires. What confuses the issue is that no relationship was observed between the MRT and recall in the linear positioning task even though both tasks are thought to engage spatial processes. It possibly demonstrates that the two tasks involve different kinds of spatial processes.

The absence of a relationship both between the questionnaire and performance data and between the questionnaire and EEG data is also explained in terms of different cognitive processes being engaged in the behavioural task and these two measures of imagery ability. Due to the restrictions imposed by the psychophysiological environment, behavioural tasks are usually very simple and have a large spatial component. It is impossible to examine gross body movement as this would introduce too much artifact into the signal. The VMIQ and MIQ involve the generation of movement images both of simple movements involving one limb and movement involving gross body movement. It

is possible that although useful in an applied setting such as sport, these measures may not be useful under the constrained conditions of psychophysiological experiments.

However, some of the questionnaire data questions the reliability of one or both of the measures used in these two experiments. There was evidence that subjects assessed the vividness of movement images generated from long term and short term memory in a similar fashion. However, this was not consistent; significant correlations between the VMIQ and MIQ were found in experiment 3 but not in experiment 4. The implication of these data is clear; in these experiments objective measures again provide more insight than movement imagery questionnaire into how neural organisation is related to individual differences in imagery ability. This is possibly a result of the fact that the items on the questionnaires do not require detailed spatial information whereas the tasks used in these experiments have a high spatial component.

8.4 Conclusion

Experiments 3 and 4 were an attempt to show how changes in cortical activity are associated with movement imagery previously found to interfere with short term memory of movement. It was hoped that they would provide objective evidence, i.e. performance and EEG data, that imagery was being used in the task. That they were unsuccessful is due to the low cognitive demands of the task and the likelihood that by changing the procedure adopted by Johnson (1982), to suit the psychophysiological environment, important information was not encoded into memory. The effect of these procedural changes serve to demonstrate the difficulties encountered when an attempt is made to incorporate neuro-imaging techniques with tasks previously found to produce specific results. These experiments also represented another attempt at showing how individual differences in imagery ability are related to changes in EEG associated with the engagement of imagery processing. Although not very powerful, the evidence suggests that measures related to performance on tasks thought to engage imagery processes

provide a more useful insight into how individual differences in imagery ability are related to cortical organisation.

Chapter 9

Does Mental Practice Improve Performance? A Further EEG Study.

In experiments 3 & 4, EEG was recorded whilst subjects were performed a task that had previously demonstrated the functional equivalence of overt and imaginary movement (Johnson, 1982). The behavioural data collected in these experiments did not replicate the findings of Johnson. One possible explanation is that changes made to the experimental procedure to accommodate psychophysiological techniques removed an important element of the task. It was also found that there were no observable changes in the EEG during an imagery condition, it being suggested that this was a result of the low demands of the task.

During these experiments it was also observed that the only measure of individual differences to demonstrate a relationship with the EEG was the MRT. Specifically, it was found that subjects with lower baseline alpha had better MRT performance. MRT was not related to EEG recorded during movement imagery or to performance on the linear

positioning task. This suggests either that these different tasks involve different aspects of spatial processing or that the linear positioning task itself, because of procedural changes. did not engage spatial processes *per se*.

Experiment 5

9.1 Introduction

Given the somewhat disappointing results of these experiments it was decided to develop a task which would have a much higher cognitive load than the linear positioning task. Even if no changes had been made to Johnson's experimental procedure, the movement involved in the task is very elementary and requires little or no programming; subjects simply move their arm from left to right. Although this was chosen to avoid the introduction of too much EMG into the signal, it may have been detrimental to other aspects of the research. Those studies that have shown that high level neural motor structures become active during movement imagery, typically used a task requiring a relatively complex sequence of movements that involves considerable internal programming (e.g. Roland *et al.*, 1980).

Experiment 1 of this thesis has shown that a task involving the transformation of images in 3D space had sufficient cognitive load to cause an observable change in the EEG. With this is mind and given that the main focus was still on movement imagery, it was decided to develop a task that involved complex sequences of movement in more than one plane. Given the severe limitations imposed on experimental design by psychophysiological techniques this is not easy; as mentioned previously, most investigations of this kind involve hand or finger movements because gross body movements introduce considerable artifact into the EEG signal. A task that has been used to produce objective evidence of the effects of movement related imagery, and which could be adapted to suit the demands

of a psychophysiological investigation was that used by Smyth and her associates (Smyth *et al.*, 1988, Smyth & Pendelton, 1989; Smyth & Scholey, 1992).

In an investigation of the spatial components of working memory, Smyth *et al.* (1988) demonstrated that performance of a secondary spatial task interfered with memory of a series of pointing movements to positions in space but did not interfere with memory of patterns of whole body movements. This was interpreted as showing that separate information is used during different types of movements. Their study used an adaptation of the Corsi blocks task (De Renzi & Nichelli, 1975) which in its original form involves the use of a set of nine blocks placed on a board in a pseudo-random order. The experimenter touches a series of blocks and the subject has to recall the sequence by touching the blocks in that same order. This task is widely regarded as a measure of spatial ability and has been used extensively in neuropsychological studies, particularly with patients who have spatial disorders following damage to the right posterior cortex. Therefore, this task is potentially useful as it is has both a motor and a spatial component. Smyth and Scholey (1992) used a computerised version of the Corsi block task; the array was presented on a touch sensitive screen and each block was illuminated in a predetermined sequence. Subjects recalled the sequence by touching, with their hand, the corresponding blocks on the screen.

As described in Chapter 2, during most mental practice (MP) studies subjects perform a pre-test on a particular task, then engage in some form of interpolated activity and finally receive a post-test assessment. The interpolated activity consists of physical rehearsal, imaginary rehearsal or control activity that is unrelated to the task. If there is a significant improvement from pre-test to post-test following either physical or imaginary rehearsal but not following the control activity, then it is assumed that this improvement is a result of this interpolated activity.

It seemed appropriate to adapt Smyth and Scholey' s design to investigate the effects of physical and imaginary rehearsal on the recall of a sequence presented on screen. This task would have a high cognitive load as it would require subjects to imagine (adopting an 'internal visual' perspective) a sequence of movements in more than one plane. It also has the benefit of not requiring gross body movements and potentially makes it suitable for an EEG investigation. It would allow a comparison of the effects of physical and imaginary rehearsal on the learning of a sequence of movements to different positions in space. It would have the additional benefit of providing the opportunity to examine changes in cortical activity that occur during learning. Seitz and Roland (1992) reported that rCBF in the superior parietal cortex and right inferior frontal cortex decreased as subjects became more proficient at a finger apposition task. It is possible that imagery of a sequence of movements would contain more accurate information when that sequence has been learned. This would imply that activity over areas of cortex thought to be involved in movement imagery would be greater once a sequence has been learned.

One of the problems inherent to imagery research is that one can never be sure that subjects do actually use imagery. One approach to this problem has been to be compare the time taken to make a series of overt movements with the time taken to imagine making those movements. A number of studies have shown that there is no difference between the imagery and overt movement (Decety, *et al.*, 1989; Decety & Michel, 1989; Landauer, 1962) demonstrating that they possess similar temporal characteristics. It was decided to compare both the duration of physical and imaginary rehearsal trials and the recall trials following each form of rehearsal. Accuracy and temporal data recorded trial by trial would provide detailed information of the effects of physical and imaginary rehearsal on recall. It would also provide additional evidence of the use of imagery.

Most of the evidence showing that neural motor structures are active during movement imagery have adopted the subtraction method to examine changes in rCBF. It seemed plausible that a similar approach could be used in psychophysiology. EEG could be

recorded during a series of control conditions that differed from the experimental conditions only with respect to the activity under investigation. This would provide an additional 'baseline' to the more frequently used 'eyes open' condition. This information, together with accuracy and temporal data, would also allow the exclusion of the traditional control condition used in MP studies. This would have the additional benefit of reducing the duration of each session which is an important consideration when recording EEG.

Behavioural Predictions

1. The accuracy of recall would improve over trials.

2. Imaginary rehearsal and physical rehearsal would result in similar learning curves over time.

3. The physical and imaginary rehearsal trials would exhibit similar temporal characteristics to each other and to the corresponding recall trials.

Psychophysiological Predictions

Most of these predictions are based on the same evidence referred to in the previous chapters.

1. There would be a reduction in power density in the alpha and beta bands over pre-frontal, posterior temporal and parieto-occipital cortex during both the encoding of a sequence and during the imaginary rehearsal of that sequence compared to an eyes open baseline and to a number of control conditions.

2. When subjects have learned the sequence they should be able to generate a more accurate and vivid image, so power density was expected to be *lower* during the last 3 trials of the *imaginary rehearsal* condition compared to the first 3 trials.

3. MRT performance was expected to predict changes in EEG activity from the baseline and control conditions to the imaginary rehearsal condition, at the cortical areas referred to above. The VMIQ and MIQ would show no relationship to task related changes in EEG or to MRT performance.

9.2 Method

Subjects

20 right handed subjects (11 male, 9 female) aged 21 - 32 (mean age 26 years) were selected from the research staff at the Defence Research Agency, Centre of Human Sciences, Farnborough. The EEG data of one of these subjects was found to be corrupted and was not included in any analysis. The remaining 19 subjects (11 male, 8 female) had a mean age of 25 years and 9 months.

Apparatus and Materials

Each subject completed the MRT (Vandenberg & Kuse, 1986), the VMIQ (Isaac *et al.*, 1986) and the adapted version MIQ (Hall *et al.*, 1985). The apparatus consisted of a Macintosh Quadra 850, a 12.5 inch Macintosh monitor and a Wacom A3 pressure sensitive pad. The latter piece of equipment involves the use of stylus which operates as a mouse. An 'in house' purpose built 'slave' system was also used allowing simultaneous control of the experimental software and an EEG trigger signal. The computer monitor and pressure sensitive pad were positioned on two tables 70 cm in height. To remove the

effects of radiation emitted by the monitor, the two tables were placed 1 m apart. See Appendix C, Figure C9.1.

Procedure

In this chapter, 3 terms (session, condition and trial) are used to denote the different elements of the experiment. EEG was recorded during three sessions; baseline, control and experimental. During the baseline session there were two eyes open trials. During the control session there were 3 conditions, each comprising one trial (encoding control; physical rehearsal control; imagery rehearsal control). There were two experimental sessions (physical rehearsal and imaginary rehearsal), each of which comprised three conditions (encoding, rehearsal and recall) made up of 10 trials, i.e.. subjects observed the sequence, rehearsed it and then physically recalled it. This whole procedure was repeated 10 times. See Table 9.1.

Table 9.1 A summary of the procedure in Experiment 5

Baseline Session	Eyes open	2 trials (1 min)
Control Session	Encoding Control	1 trial (40 secs)
	Imagery Control	1 trial (40 secs)
	Recall Control	1 trial (40 secs)
Experimental Session		
a) Physical Rehearsal	Encoding	10 trials
	Physical rehearsal	10 trials
	Recall	10 trials
b) Imaginary Rehearsal	Encoding	10 trials
	Imaginary rehearsal	10 trials
	Recall	10 trials

1. Baseline Session

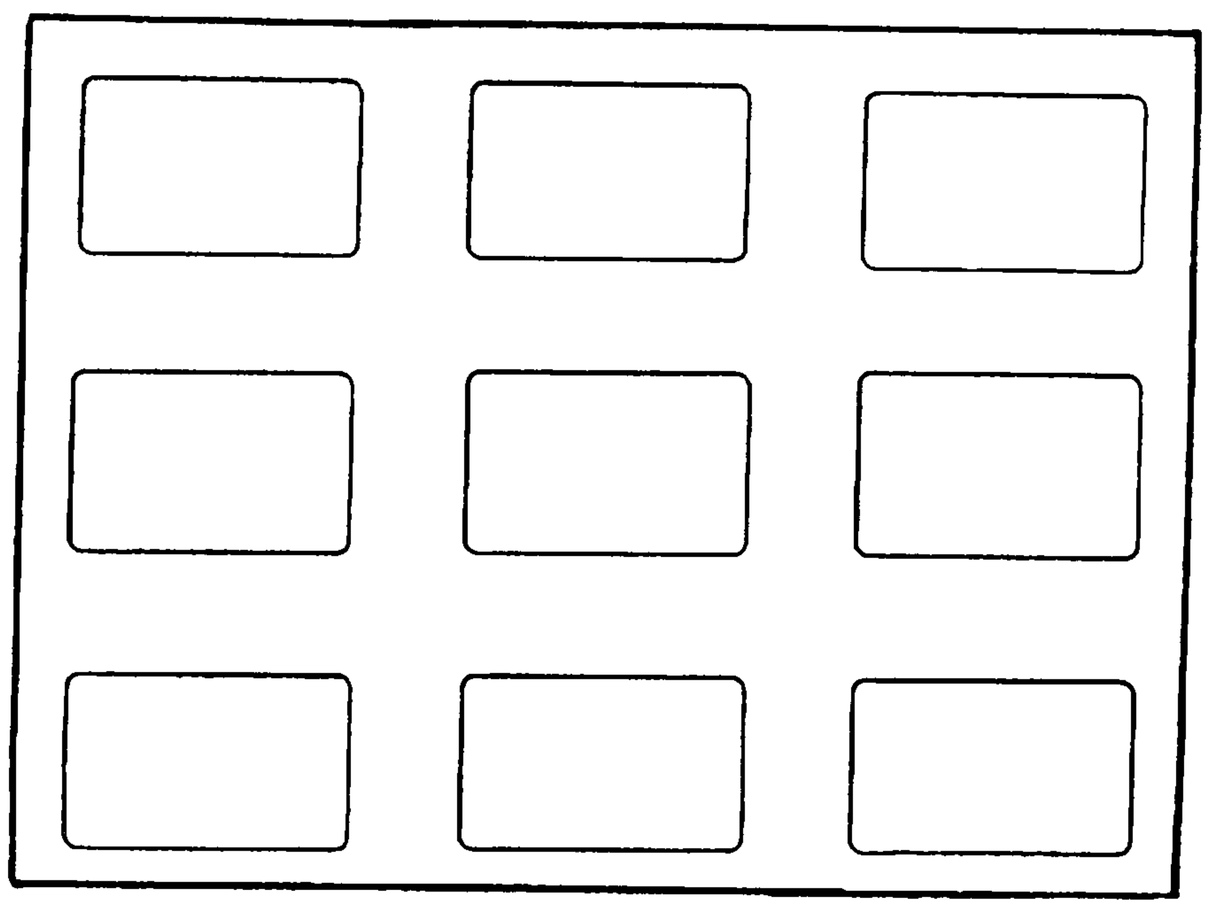
Interviews following Experiment 3 revealed that subjects had found it uncomfortable to keep their eyes open for two minutes under instructions to keep blinks to a minimum. It was therefore decided to record two, one minute baselines. EEG was recorded during two 1 minute eyes open (EO) trials. Subjects heard one 'beep' denoting that the trial had begun and two 'beeps' informing them that it had ended. Each baseline was separated by a forty second interval. Instructions during these trials were identical to those given in previous experiments.

2. Control Session

a) *Encoding Control (CON 1)*

Subjects were instructed to look at the computer monitor on which a 3*3 matrix of rectangular blocks was presented. See Figure 9.1

Figure 9.1 Illustration of 3*3 Matrix



Each block measuring 5.9 x 3.6 cm was then illuminated according to a random sequence generated by the experimental software. The blocks were illuminated for one second with a 0.5 second delay between one being 'switched off' and the next one being 'switched on'. Subjects heard one 'beep' denoting that the trial had begun and two 'beeps' informing them that it had ended. Subjects were instructed to attend to the sequence but without trying to remember it. Great emphasis was placed on subjects attending to the display without moving their eyes; to that end they were instructed to look at the centre block but still attend to the sequence. The duration of the trial was 40 seconds during which time EEG was recorded.

b) *Imagery Control (CON 2)*

Subjects were instructed to look at the pressure sensitive pad on which an identical 3*3 matrix of rectangular blocks was drawn. Again, emphasis was placed on reducing muscle contamination so they were instructed to look at the centre block during the trial and attend to the other blocks but without moving their eyes. EEG was recorded for the duration of the trial (40 seconds), the beginning and end of which was denoted by one 'beep' and two 'beeps' respectively.

c) *Recall Control (CON 3)*

EEG was recorded while subjects touched each of the blocks drawn on the pad using the accompanying stylus. The trial began when subjects touched the first block and ended 40 seconds later when they heard two 'beeps'. They were told to look at the centre block while making the movements and attempt to touch each block at the same rate as they were flashed on screen during Control 1.

These control conditions were always presented in the same order. As it was important that subjects physically or imagined touching each block at a particular rate, it was important that the encoding sequence was presented first.

3. Physical Practice Session

Encoding condition

The same 3*3 matrix was generated on the monitor. After a one second delay each of the nine blocks was illuminated according to a sequence randomly generated by the software, the timing being identical to that described in Control 1. See Appendix C, Figure C9.2. Subjects were instructed to remember the 9 item sequence. On completion of the sequence a single tone 'beep' was sounded indicating that subjects had to physically rehearse the sequence.

Physical rehearsal condition

Subjects were instructed to rehearse the sequence by touching, with the stylus, the corresponding blocks on the pad at approximately the same rate as they were flashed on screen. On completion of their rehearsal trial there was then a five second delay.

Recall condition.

Subjects then heard a two tone 'beep' indicating they had to recall the sequence. Subjects again touched the corresponding blocks using the stylus and pad.

At the end of each recall condition there was a one second delay and the same sequence was again generated on the computer monitor. The encoding, physical rehearsal and recall conditions were repeated ten times, the EEG being recorded during each trial. The sequence generated by the software, the accuracy of the subjects during rehearsal and recall together with the time taken to repeat the sequence during each trial of the rehearsal and recall condition were recorded to a text file.

4. Imaginary rehearsal Session

Encoding condition

The same 3*3 matrix was generated on the monitor. After a one second delay each of the nine blocks was illuminated according to a sequence randomly generated by the software (different to that generated in the physical practice session), the timing being identical to that described in Control 1. Subjects were instructed to remember the 9 item sequence.

Imaginary rehearsal condition

Subjects then looked at the pad and were required to mentally rehearse the encoded sequence by imagining themselves touching each block with the stylus, at the same rate as the blocks were flashed on screen. The rehearsal condition started when subjects

indicated that they had generated an image by touching the pad once with the stylus. It ended when they touched the pad a second time. There was then a five second delay.

Recall condition:

Subjects heard a two tone 'beep' indicating that they had to recall the sequence, again by touching the corresponding blocks on the pad with the stylus.

At the end of each recall condition there was a one second delay and the same sequence was again repeated on the computer monitor. The presentation, imaginary rehearsal and recall conditions of this rehearsal session was repeated ten times. The sequence generated by the software, the accuracy of recall and the time taken both to mentally rehearse and physically recall the movement sequence were recorded to a text file.

The presentation of the physical and imaginary rehearsal session was counterbalanced across subjects.

Apparatus and EEG Recording

The EEG equipment and recording settings are described in chapter 5.

9.3 Results

9.3.1 Behavioural Data

It is important to note that the accuracy and temporal data for one subject was corrupted and so the statistical analysis of these data sets reported in 9.1.3a and 9.1.3b are in relation to 18 subjects.

9.3.1.1 Accuracy of Recall

It is possible to assess the accuracy of subjects' recall on the spatial span task in two ways. The first is to record the *mean number of items recalled in serial order* beginning at the first item: the second is to record the *mean number of items correctly recalled* irrespective of whether subjects went out of sequence. The second method is used as sequences of movement are not always learned in a serial order, the middle items of a sequence often being stored before initial items. The mean and standard deviations of recall following physical and imaginary rehearsal using both methods of assessment are presented in Table 9.2.

Table 9.2 Mean Accuracy and Standard Deviation of Recall following Physical and Imaginary rehearsal

a) Recall following Physical Rehearsal (Serial Recall)

	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}
Mean	2.17	3.56	6.11	7.06	7.56	7.50	8.56	7.61	8.06	8.28
SD	2.71	3.43	3.32	3.13	2.91	2.79	0.92	2.64	2.60	1.96

b) Recall following Physical Rehearsal (Mean Recall)

	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}
Mean	3.00	4.22	6.78	7.33	8.17	7.84	8.56	7.94	8.33	8.28
SD	2.83	3.12	2.86	2.87	1.62	2.12	0.92	1.89	1.85	1.96

c) Recall following Imaginary rehearsal (Serial Recall)

	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}
Mean	2.53	4.68	5.10	6.05	7.68	6.89	8.00	8.47	7.95	7.95
SD	3.34	3.50	3.46	3.26	2.40	3.03	2.03	1.43	2.37	2.32

d) Recall following Imaginary rehearsal (Mean Recall)

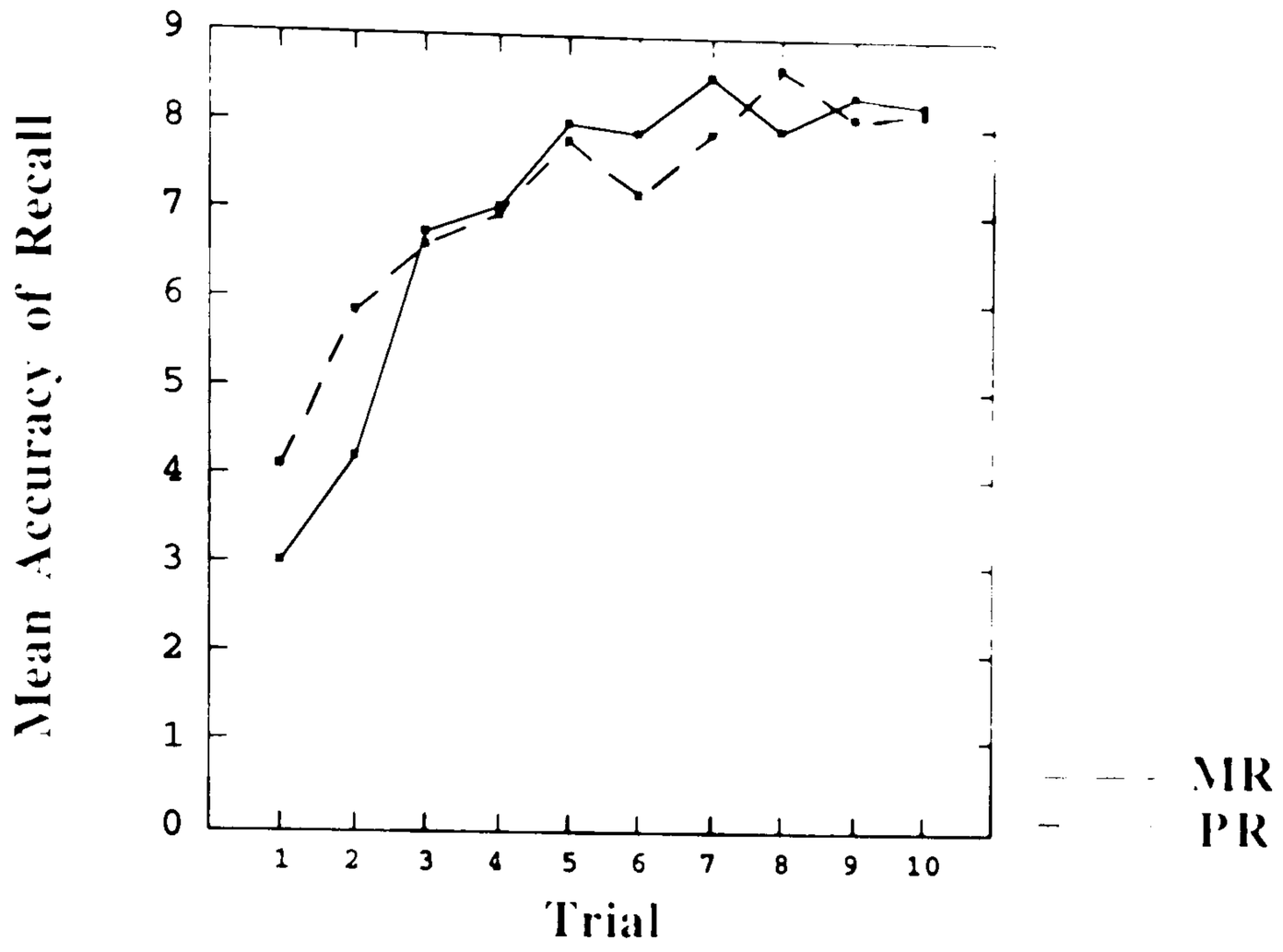
	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}
Mean	4.10	5.74	6.42	6.79	7.84	7.00	8.00	8.68	8.32	8.16
SD	3.02	3.05	2.67	2.48	2.17	2.69	2.03	0.82	1.42	2.01

T = Trial

Table 9.2 shows that accuracy of recall following physical and imaginary rehearsal, assessed either by serial or mean recall, shows very similar trends across the ten trials. To determine whether there was any significance differences both between the accuracy of recall following physical and imaginary rehearsal and between the different methods used to assess accuracy, a 4 x 10 MANOVA was conducted using condition (recall following physical rehearsal [serial recall x mean recall] x (recall following imaginary rehearsal [serial recall x mean recall]) x trial number, as variables. This was followed by appropriate univariate analyses.

The most important aspect of this analysis was in relation to the various conditions: MANOVA indicated a significant effect of condition [$F(3, 51) = 21.41$, $p < 0.0005$]. Post hoc analysis of the condition effect showed no significant difference between the accuracy of recall following physical or imaginary rehearsal. A significant difference in the accuracy was found between serial and mean recall following both physical rehearsal ($p = 0.023$) and imaginary rehearsal ($p = 0.001$). Given this finding, it is argued that mean recall provides a more accurate measure of accuracy and so it was decided to restrict further analysis using this method. A diagrammatical representation of subjects' accuracy following physical and imaginary rehearsal, assessed by mean recall is presented in Figure 9.2.

Figure 9.2 A comparison of the accuracy of recall following mental and physical rehearsal



MR = Recall after Mental Rehearsal
PR = Recall after Physical Rehearsal

Figure 9.2 shows recall was poor during the first 2 trials but improved dramatically over the next two trials. However, although there is a slight increase in mean recall from trial 3 this increase is not significant. A 2 x 10 MANOVA was conducted with condition (recall following physical rehearsal x recall following imaginary rehearsal) x trial, as variables. This analysis confirmed the absence of any difference in recall between the two practice conditions but showed a significant effect of trial [$F(9,153) = 23.53$, $p < 0.0005$]. No interaction was observed. Post hoc analysis showed that there was no significant increase in mean accuracy of recall after trial 3.

9.3.1.2 Temporal Data

The mean times taken to mentally rehearse (MR) and physically rehearse (PR) the sequence during each of the ten trials are presented in Table 9.3.

Table 9.3 Mean Duration of Physical and Imaginary rehearsal of the Sequence

a) Mean Duration (secs) of Physical Rehearsal

	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}
Mean	10.39	9.85	9.21	9.35	9.14	9.74	9.23	8.69	9.20	9.00
SD	1.87	2.11	1.86	1.63	1.46	1.65	1.07	2.20	1.82	1.70

b) Mean Duration (secs) of Imaginary rehearsal

	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}
Mean	10.18	9.58	11.32	11.81	10.34	10.29	8.68	8.51	8.90	9.18
SD	5.03	3.73	4.13	6.45	4.50	3.80	4.64	4.89	4.10	4.09

Table 9.3 demonstrates that the time taken to physically rehearse the sequence is similar across all ten trials and that there is very little inter-subject variation. The time taken to mentally rehearse the sequence, however, does not demonstrate the same consistency across the trials. Up to trial 7 the duration of the imagined sequence is longer than the time taken to physically rehearse the sequence, after which point there appear to be similar times in both conditions. It is also evident that there is considerably higher inter-subject variation in the imaginary rehearsal condition compared to the physical rehearsal

condition. A diagrammatical representation of the mean times taken to physically and mentally rehearse the sequence is presented in Figure 9.3.

Figure 9.3 A comparison of the mean duration of mental and physical rehearsal

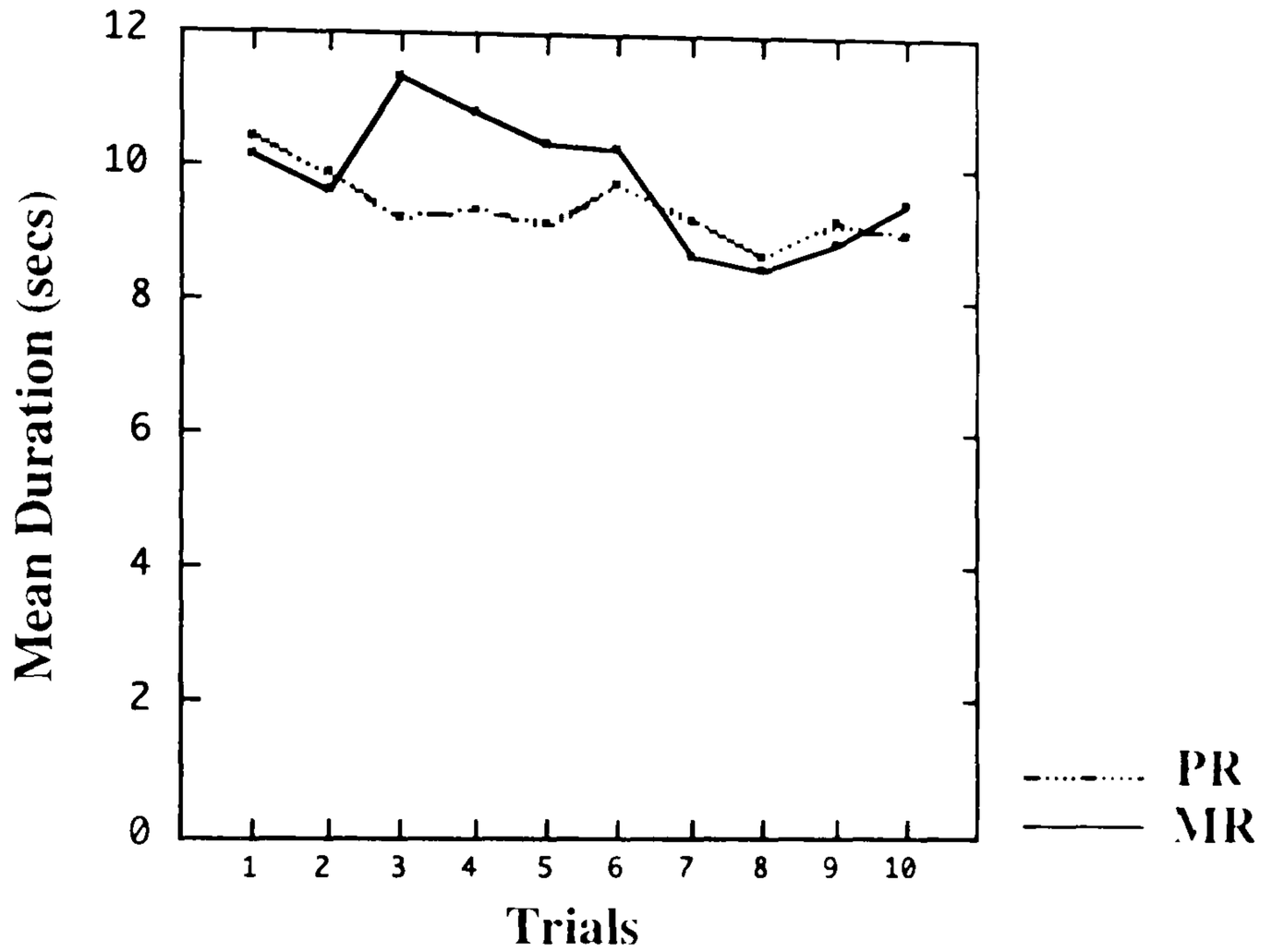


Figure 9.3 demonstrates that apart from the increase in time in MR during trials 3-6 both sets of data follow similar trends. To determine whether there was any statistically significant differences in the duration of both the rehearsal and recall conditions, a 4 x 10 MANOVA was conducted with condition [physical rehearsal x imaginary rehearsal x recall (physical) x recall (mental)] x trial, as variables. Results showed that there was no condition effect, no effect of trial and no interaction indicating that mean duration of the trials was similar in all conditions.

condition. A diagrammatical representation of the mean times taken to physically and mentally rehearse the sequence is presented in Figure 9.3.

Figure 9.3 A comparison of the mean duration of mental and physical rehearsal

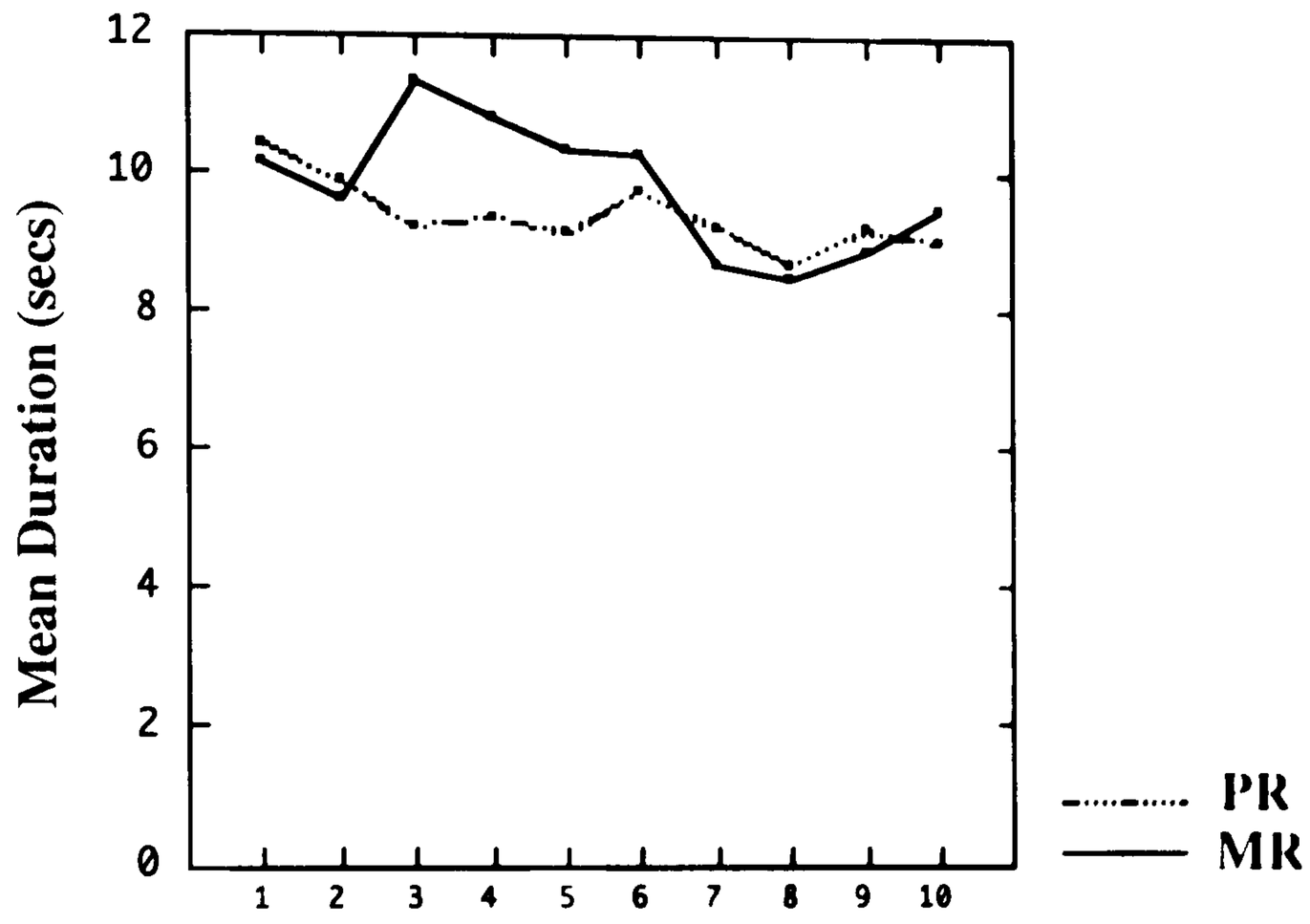


Figure 9.3 demonstrates that apart from the increase in time in MR during trials 3-6 both sets of data follow similar trends. To determine whether there was any statistically significant differences in the duration of both the rehearsal and recall conditions, a 4 x 10 MANOVA was conducted with condition [physical rehearsal x imaginary rehearsal x recall (physical) x recall (mental)] x trial, as variables. Results showed that there was no condition effect, no effect of trial and no interaction indicating that mean duration of the trials was similar in all conditions.

9.3.1.3 Individual Differences

The means and standard deviations of the VMIQ, the MIQ and the MRT are presented in Table 9.4

Table 9.4 Summary of means and standard deviations of the VMIQ, MIQ and MRT.

	VMIQ__T	VMIQ_K	VMIQ_V	MIQ_T	MIQ_K	MIQ_V	MRT
Mean	116.42	62.58	53.84	40.26	19.05	21.21	14.47
SD	37.80	19.28	21.23	22.77	9.44	14.14	4.18

T = Total

K= Kinaesthetic Imagery Score

V = Visual Imagery Score

A low score indicates a vivid image and the mean scores of sub-scales in both the VMIQ and MIQ are below the mid point. Table 9.4 shows that subjects rate both visual and kinaesthetic images as having a high degree of vividness. Subjects' performance on the MRT is also good demonstrating that on average this group have good spatial ability.

A series of correlations using the Pearson product moment coefficient were performed between the VMIQ, MIQ and MRT. No relationship was found between performance on the MRT and self report imagery ability according to the VMIQ ($r = -0.024$, $p > 0.05$) or the MIQ ($r = 0.101$, $p > 0.05$). No relationship was found between the VMIQ and the MIQ, ($r = -0.167$, $p > 0.05$). An examination of the visual imagery and kinaesthetic components of each individual questionnaire showed that there no relationship between the visual sub-scales ($r = -0.031$, $p > 0.05$) nor the kinaesthetic sub-scales ($r = -0.211$, $p > 0.05$) of both questionnaires. There was a strong relationship between the visual and

kinaesthetic components of the VMIQ (r = 0.74, p < 0.0005) and the MIQ (r = 0.86, p < 0.005). See Figure 9.4 for an illustration of the relationship between these sub-scales of the MIQ.

Figure 9.4 The relationship between the visual and kinaesthetic components of the MIQ

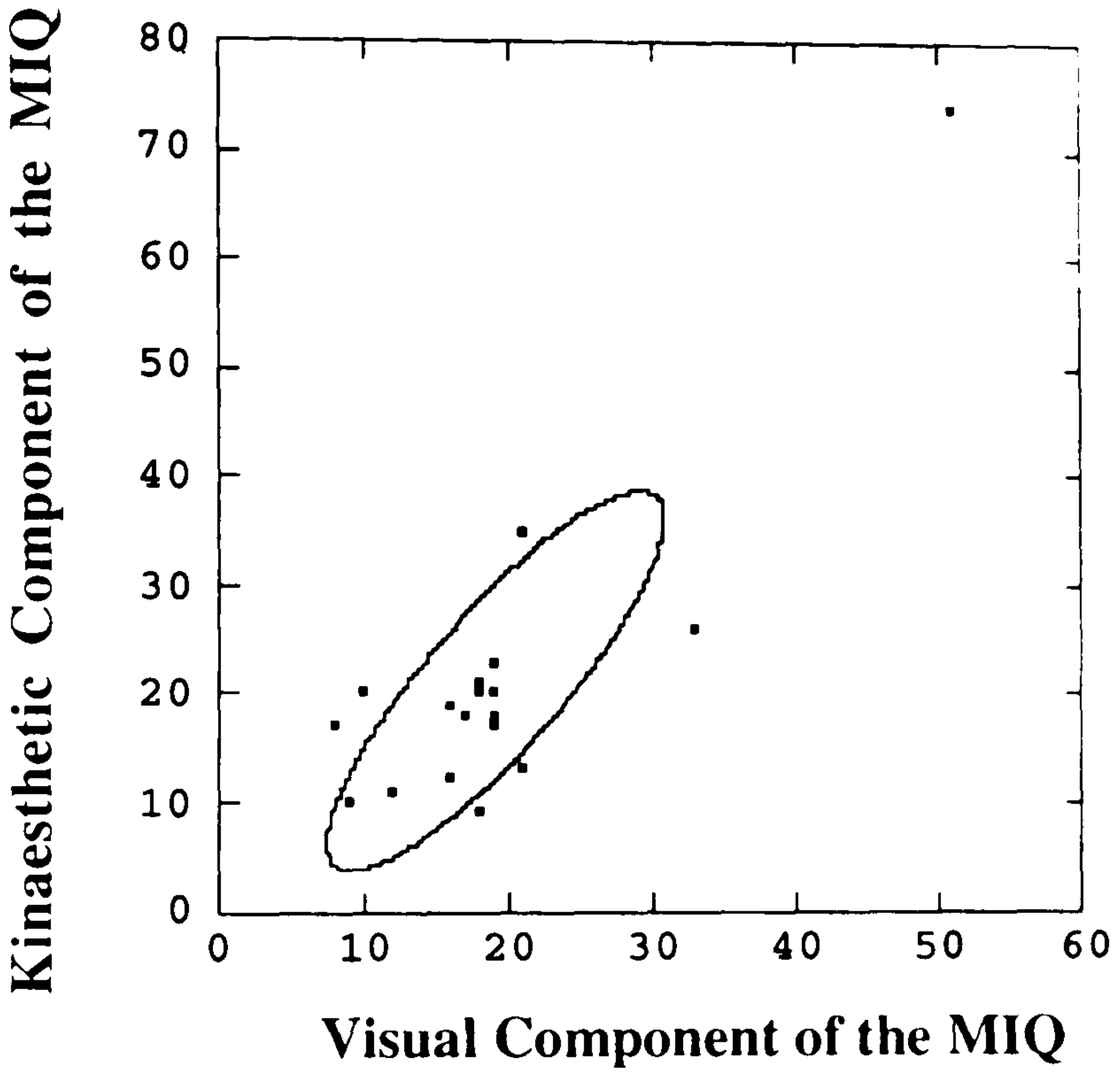


Figure 9.4 suggests that representations of movement images are comprised both of visual and kinaesthetic information. That a similar relationship was found between the two sub-scales of the VMIQ supports such a suggestion. The absence of any relationship between the two questionnaires supports the results of experiment 4 but contradict those of experiment 3.

9.3.2 Psychophysiological data

An examination of the EEG showed that there was considerable muscle related artifact during conditions that involved movement, so it was not possible to use these data in any analysis. This was in direct contrast to experiments 3 and 4, but the task in this experiment was designed so that the sequence of movements would be more complex than those made in the linear positioning task. Only the EEG recorded during the baseline session, during Control 1 and Control 2 and during the encoding and rehearsal condition of the *imaginary rehearsal session* was analysed. If an individual channel was found to be 'noisy' during any of these trials it was excluded from analysis.

Given the hypotheses stated set out in 9.1.1 the data from five anterior electrodes (F3, Fz, F4, F7 and F8) and eight posterior electrodes (T5, P3, Pz, P4, T6, O1, Oz and O2) were downloaded for more detailed analysis. Additional occipito-parietal variables (P3O1, P4O2) were derived by calculating the mean power density at these sites [e.g. P3O1 = (P3 + O1) /2]. Output from the imager provided spectral power values ($\mu V2$) in bins of 0.5 Hz and from these power density values ($\mu V2/Hz$) were calculated in the alpha, beta 1 and beta 2 frequency bands (see Chapter 5). The data in all 3 frequency bands were found to be skewed and were log transformed prior to further analysis to normalise their distributions.

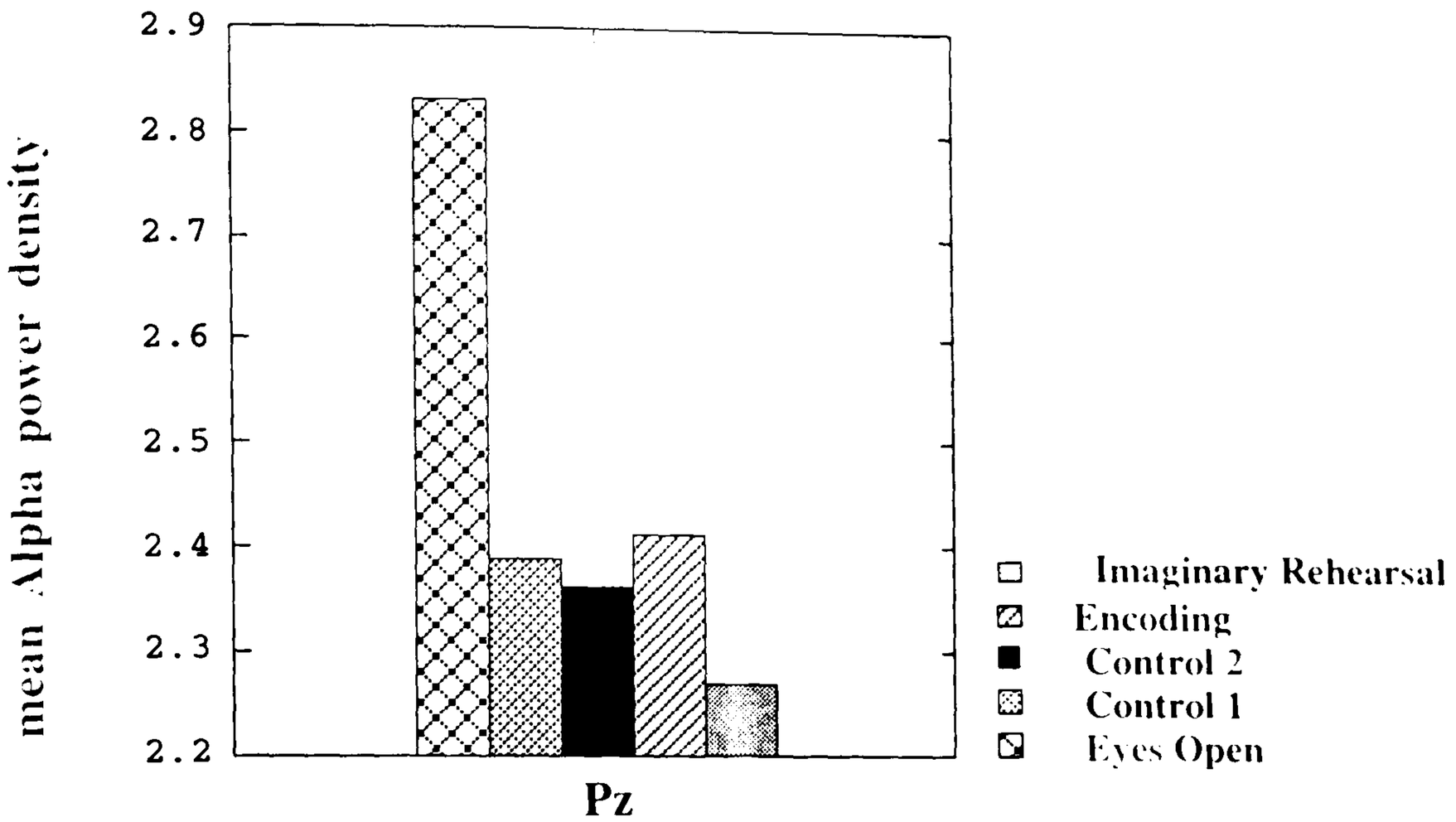
A minimum of 10 artifact free epochs (20 secs) from each subject in each condition was used in the analysis. The mean power density of each eyes open (EO) trial were summed and divided by the number of trials; the mean duration of the EO condition was 17 epochs (34 secs). The mean duration of the 2 control conditions (Control 1 and Control 2) was 14 epochs (28 secs) and 15 (secs) respectively. During the encoding (EN) and imaginary rehearsal (IR) conditions the mean power density was calculated across all 10 trials; the mean duration of EEG in these conditions was 33 epochs (66 secs) and 24 epochs (48 secs) respectively.

MANOVAs were conducted with condition (eyes open baseline x control 1 x control 2 x encoding x imaginary rehearsal) and site (the 15 electrodes specified above) as variables. This was followed by repeated measures univariate ANOVAs and the appropriate post hoc tests. The regression and correlational analyses outlined in Chapter 5 were also applied to the data.

Alpha

The means and standard deviations of power density at each electrode in the alpha frequency band during each condition of the experiment are presented in Appendix A. Table A9.1. This table shows that at most of the electrodes, there is higher power density (lower activity) during EO compared to that recorded during the other sessions. It also shows that with the exception of occipital electrodes there appear to be very little difference between the EN and IR condition and their respective control sessions (CON 1 and CON 2). See Figure 9.5.

Figure 9.5 Alpha Power density recorded at Pz during all five conditions

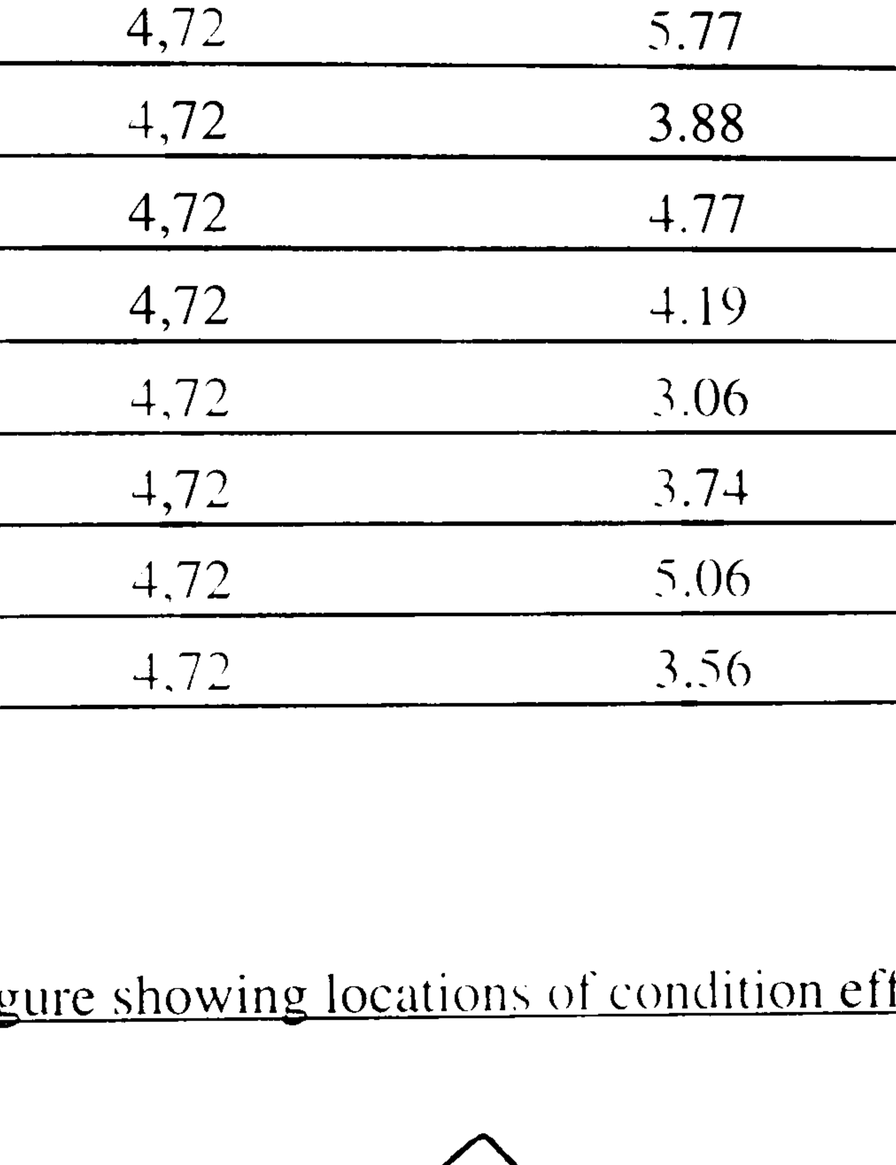


MANOVA indicated a significant effect of condition [F (4,72) = 70.138, $p < 0.0005$]. Repeated measures ANOVAs were performed on data recorded at each electrode during each experimental condition. Significant effects were found at a number of sites, the details of which are summarised in Table 9.5. Those electrodes which showed significant differences are shown in Figure 9.6.

Table 9.5 Electrodes at which condition effects were observed in alpha

Electrode	d.f.	F -ratio	p
F7	4,72	5.78	0.002
Fz	4,72	4.54	0.009
F8	4,72	3.82	0.02
T5	4,72	5.72	0.002
P3	4,72	5.77	0.004
Pz	4,72	3.88	0.007
T6	4,72	4.77	0.007
O1	4,72	4.19	0.018
Oz	4,72	3.06	0.05
O2	4,72	3.74	0.02
P3O1	4,72	5.06	0.009
P4O2	4,72	3.56	0.03

Figure 9.6 Figure showing locations of condition effects in alpha



A summary of post hoc analysis is presented in Table 9.6

Table 9.6a Electrodes demonstrating a change in alpha from the Eyes Open baseline to the Control 1 condition

Electrode	Condition	p (Tukey)
F7	EO - CON 1*	0.004
Fz	EO - CON 1*	0.001
T5	EO - CON 1*	0.0006
P3	EO - CON 1*	0.006
Pz	EO - CON 1*	0.04
T6	EO - CON 1*	0.007
O1	EO - CON 1*	0.003
Oz	EO - CON 1*	0.024
O2	EO - CON 1*	0.008
P3O1	EO - CON 1*	0.004
P4O2	EO - CON 1*	0.024

Table 9.6b Electrodes demonstrating a change in alpha from the Eyes Open baseline to the Control 2 condition

Electrode	Condition	p (Tukey)
F7	EO - CON 2*	0.05
T5	EO - CON 2*	0.02
P3	EO - CON 2*	0.003
Pz	EO - CON 2*	0.02
O1	EO - CON 2*	0.05
P3O1	EO - CON 2*	0.014

Table 9.6c Electrodes demonstrating a change in alpha from the Eyes Open baseline to the Encoding condition

Electrode	Condition	p (Tukey)
T5	EO - EN*	0.005
P3	EO - EN*	0.012
T6	EO - EN*	0.026
P3O1	EO - EN*	0.041

Table 9.6d Electrodes demonstrating a change in alpha from the Eyes Open baseline to the Imaginary Rehearsal condition

Electrode	Condition	p (Tukey)
Fz	EO - IR*	0.01
T5	EO - IR*	0.001
P3	EO - IR*	0.001
Pz	EO - IR*	0.003
T6	EO - IR*	0.004
O1	EO - IR*	0.009
O2	EO - IR*	0.01
P3O1	EO - IR*	0.003
P4O2	EO - IR*	0.012

* indicates lower power density during that condition

EO = Eyes Open Condition

CON 1 = Control 1

CON 2 = Control 2

EN = Encoding

IR = Imaginary Rehearsal

In summary, Table 9.6 shows that power density is lower in both control and experimental conditions compared to the EO baseline, suggesting that subjects' attention levels are higher during these conditions. The changes in power density are primarily over pre-frontal and parieto-occipital sites, demonstrating that there is a generalised state of activation during these conditions. No differences in power density were observed between the experimental conditions and their respective control conditions. As stated earlier, the control conditions were included as the subtractive approach may provide more insight into task related changes in EEG. The assumption of the subtractive method is that the two tasks differ with regard to only one component, which in this case is imagery. The evidence of this study suggests that the EEG, in contrast to rCBF methods, may not be sensitive enough to detect changes that reflects *just* imagery processes.

The fact remains that there was a significant decrease in alpha power density during IR compared to EO over the pre-frontal cortex and over the parieto-occipital cortex. To investigate the relationship of individual differences in imagery ability to EEG activity by treating EO as a genuine baseline of activity. Two new variables were derived by subtracting power density recorded during baseline conditions from the experimental conditions, i.e. (EN - EO) and (IR - EO). Each of these new variables was then treated as the dependent variable in separate multiple regression analyses. Only MRT predicted consistently the change in power density from EO to both EN and IR. A summary of the regression analyses is presented in Table 9.7.

Table 9.7 Summary of Multiple Regression analyses in the alpha frequency

a) Encoding

	Coefficient	t	p	Spr (%)
T6	0.013	3.27	0.005	41

b) Imaginary rehearsal

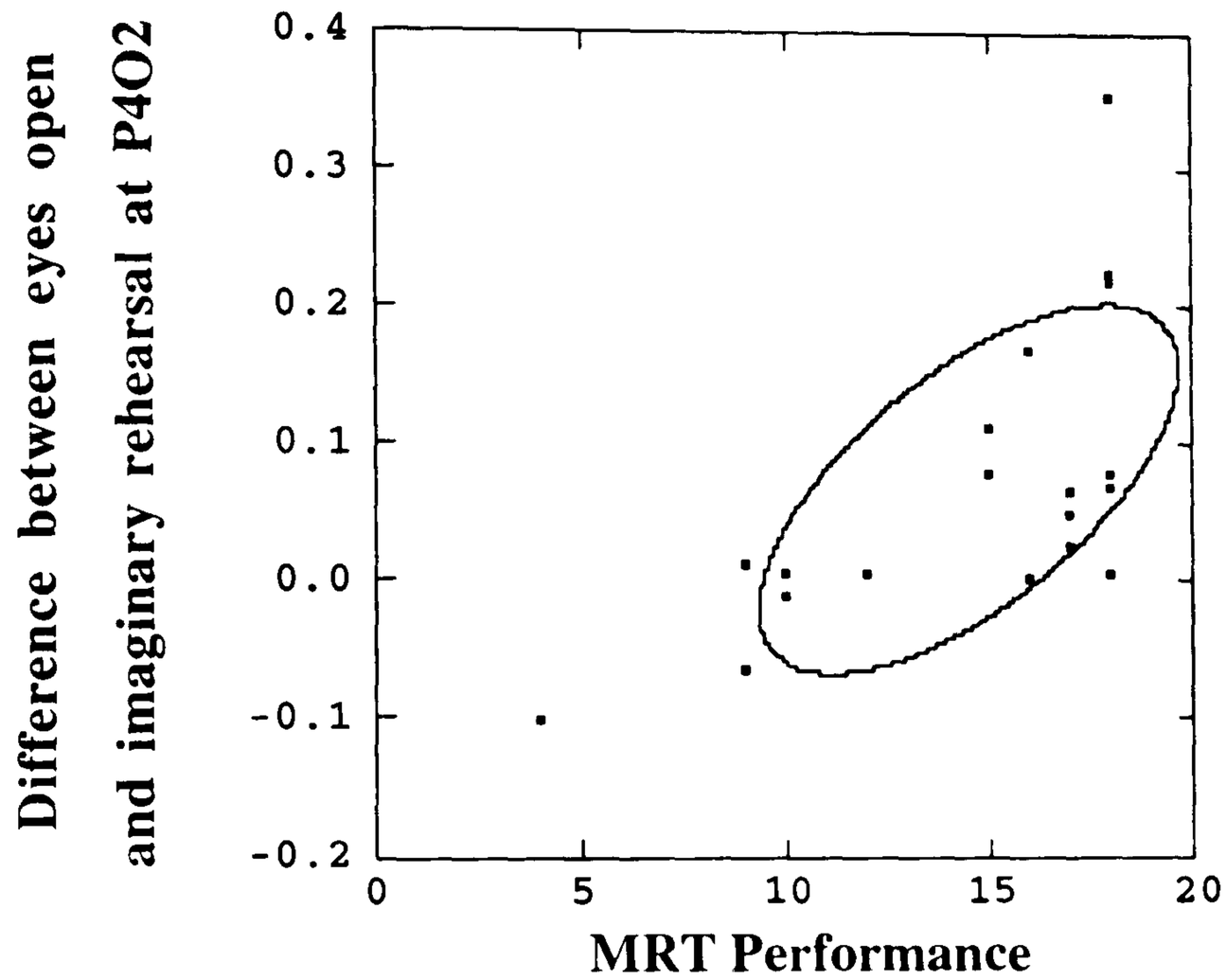
P4O2	0.018	3.66	0.002	46

Spr = Semi-partial correlation coefficient

Table 9.7 demonstrates that a relationship between MRT performance and changes in power density was only observed only over the right temporo-parieto-occipital cortex. In each case this relationship was positive, implying that as MRT performance improves the difference between the power density recorded during each condition gets larger. This suggests that those subjects who are better at MRT performance have lower power

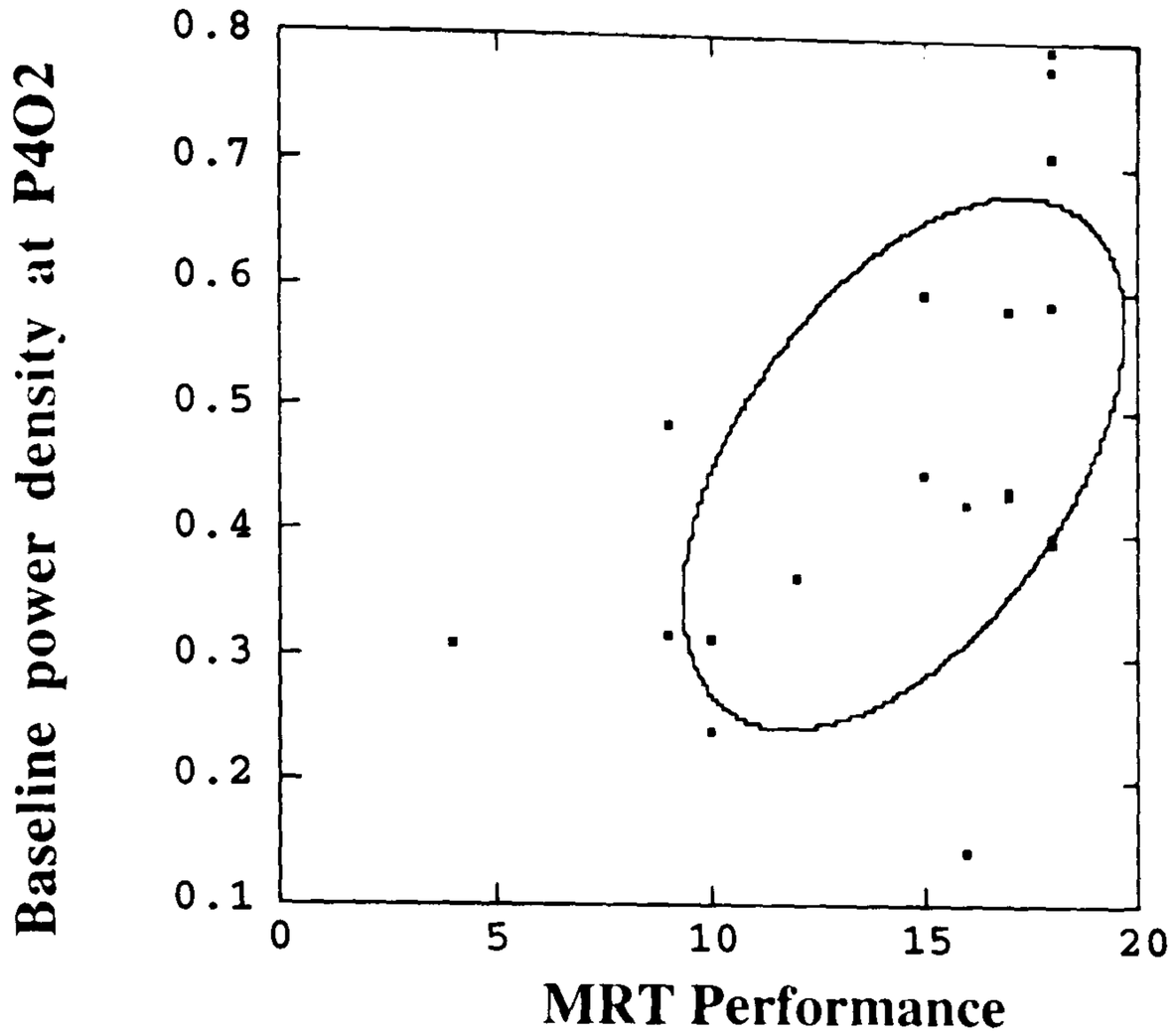
density (greater activation) over the right posterior hemisphere, during encoding and imaginary rehearsal of the sequence. See Figure 9.7.

Figure 9.7 The relationship between MRT performance and imagery related changes in alpha



Pearson correlations were performed between the MRT data and the EEG recorded during the EO, EN and IR conditions Results showed that there was a significant correlation between MRT performance and power density recorded during EO at P4O2 ($r = 0.53$, $p = 0.02$) but not at T6. No relationship was found between MRT performance and EEG activity recorded during EN or IR. The relationship between alpha activity at P4O2 recorded during the EO and MRT performance can be seen in Figure 9.8

Figure 9.8 Correlation of alpha Power density at P4O2 with MRT performance

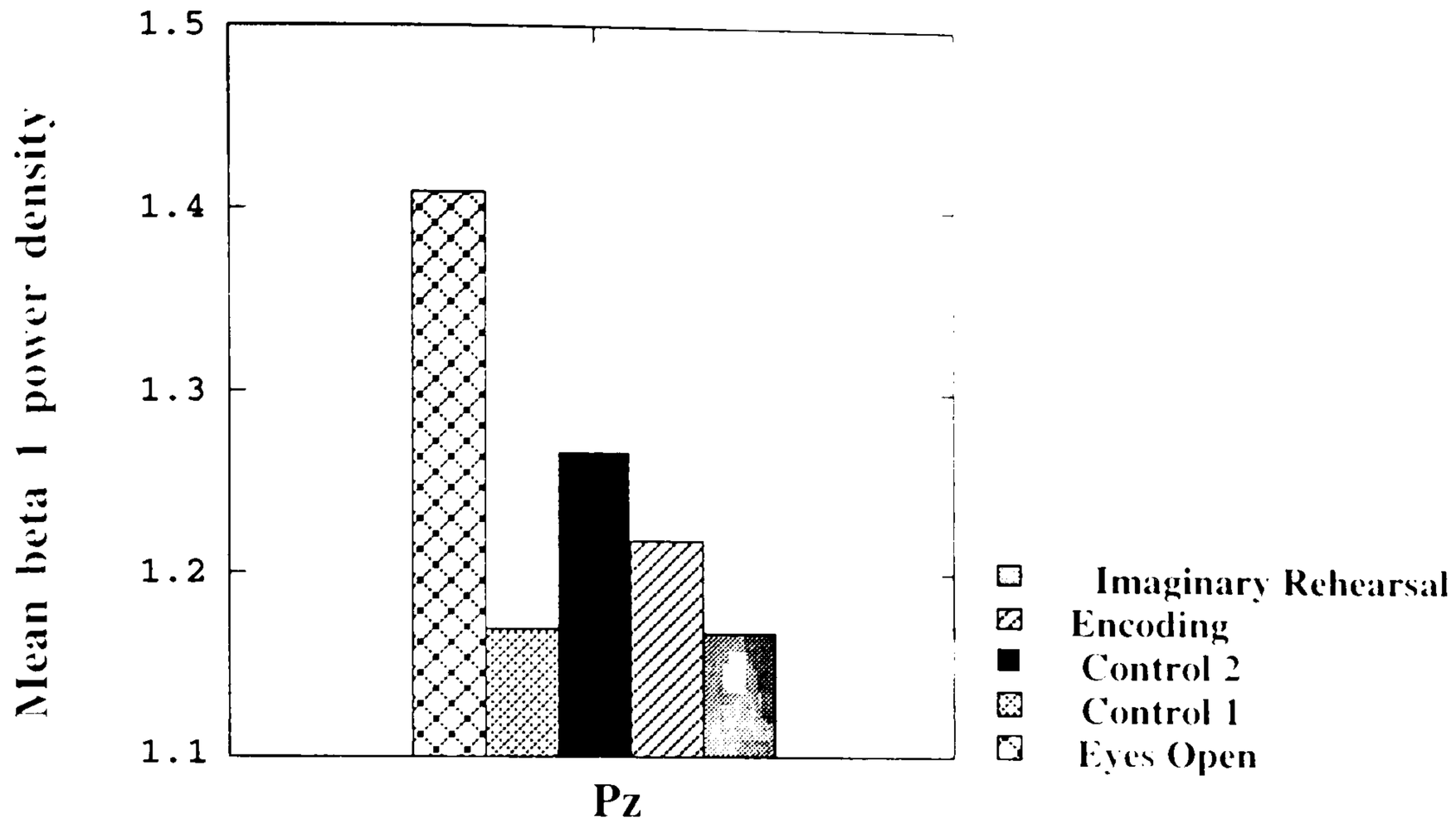


It is clear from Figure 9.8 that as MRT performance improves baseline power density increases, a relationship which is different that is opposite to that found in Experiment 3 (see Figures 8.7 and 8.8).

Beta 1

The means and standard deviations of power density at each electrode in the beta 1 frequency band during each experimental condition are presented in Appendix A, Table A9.2. An examination of this table shows that power density is lower compared to that observed in the alpha frequency. It also suggests that over the anterior region, power density is greater in EN and IR compared to EO, but at more posterior sites it is higher during EO compared to the other conditions of the experiment. See Figure 9.9.

Figure 9.9 Beta 1 Power density recorded at Pz during all five conditions

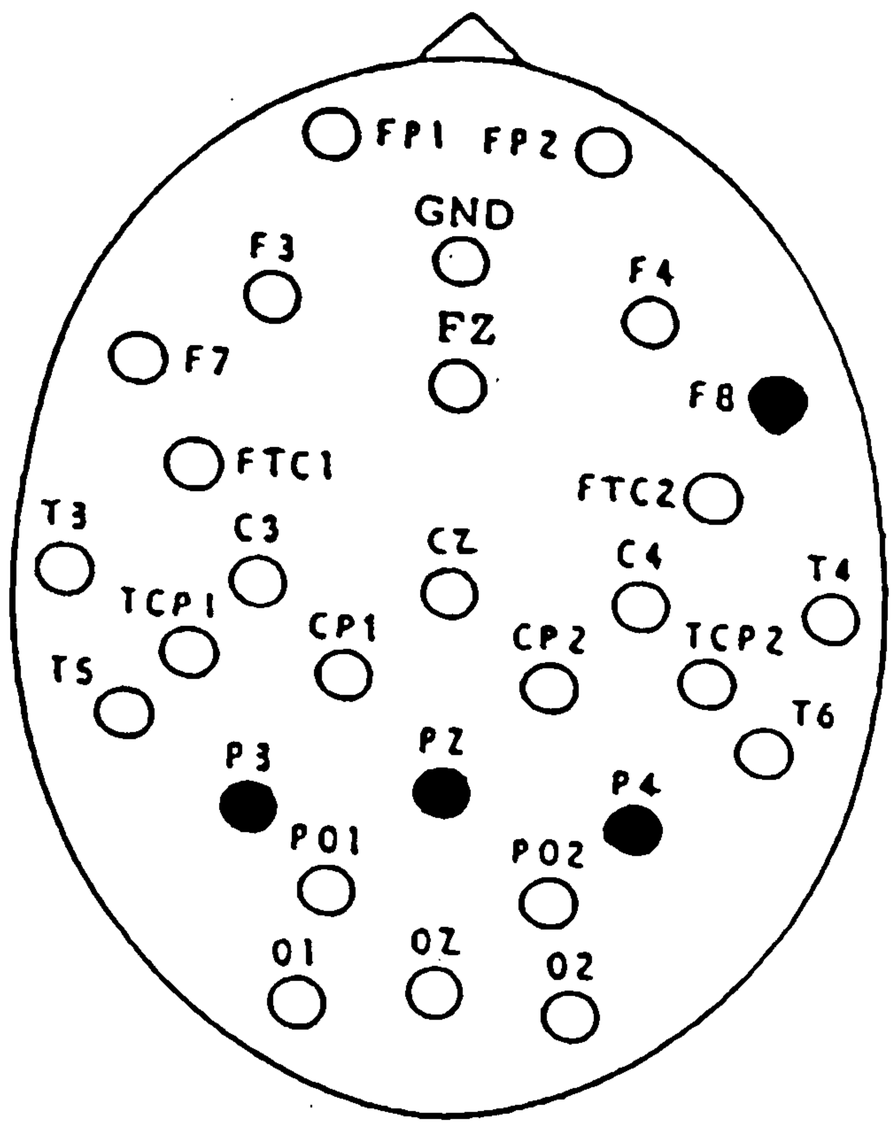


The above figure shows that power density is highest during EO. It is also worth noting that power density is higher during EN compared to its control condition (Control 1). However, power density is lower during IR compared to its control condition (Control 2). MANOVA indicated a significant effect of experimental condition [$F(4,72) = 9.807$, $p < 0.001$]. Repeated measures ANOVAs were performed on data recorded at each electrode during each of the five conditions. Significant condition effects were found at a number of sites, the details of which are summarised in Table 9.8. Those electrodes which showed significant differences are shown in Figure 9. 10

Table 9.8 Electrodes at which condition effects were observed in beta 1

Electrode	d.f.	F -ratio	p
F8	4,72	4.15	0.01
P3	4,72	5.22	0.005
Pz	4,72	7.16	0.0005
P4	4,72	2.92	0.04

Figure 9.10 Figure showing locations of condition effects in beta 1



A summary of post hoc analysis is presented in Table 9.10.

Table 9.9a Electrodes demonstrating a change in beta 1 from the Eyes Open baseline to the Control 1 condition

Electrode	Condition	p (Tukey)
P3	EO - CON 1*	0.001
Pz	EO - CON 1*	0.0001
P4	EO - CON 1*	0.041

Table 9.9b Electrodes demonstrating a change in beta 1 from the Eyes Open baseline to the Control 2 condition

Electrode	Condition	p (Tukey)
F8	EO - CON 2*	0.003
Pz	EO - CON 2*	0.04

Table 9.9c Electrodes demonstrating a change in beta 1 from the Eyes Open baseline to the Encoding condition

Electrode	Condition	p (Tukey)
Pz	EO - EN*	0.003

Table 9.9d Electrodes demonstrating a change in beta 1 from the Eyes Open baseline to the Imaginary Rehearsal condition

Electrode	Condition	p (Tukey)
P3	EO - IR*	0.01
Pz	EO - IR*	0.0002

* indicates lower power density during that condition

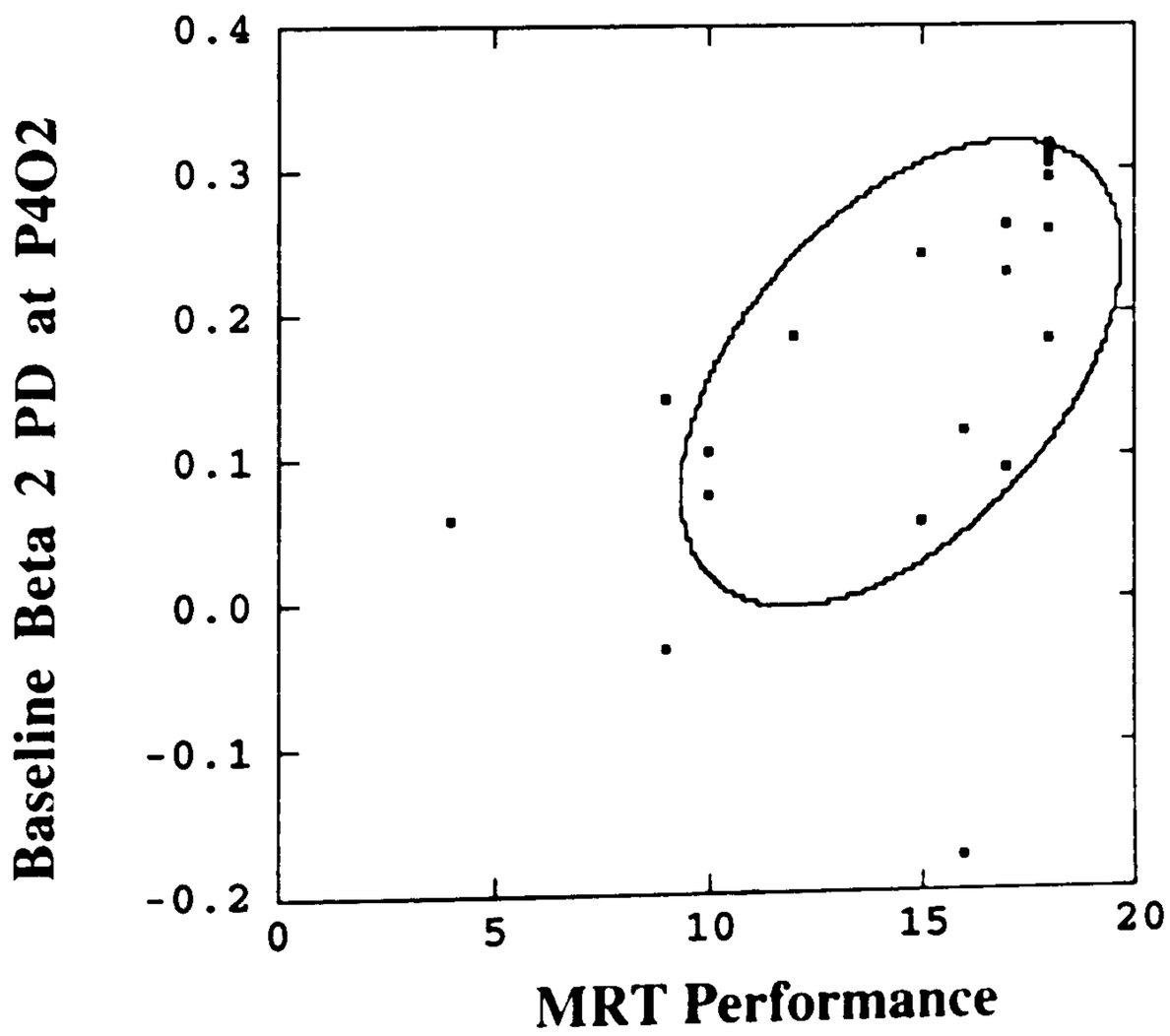
EO = Eyes Open Condition CON 2 = Control 2

EN = Encoding CON 1 = Control 1 IR = Imaginary Rehearsal

In summary, Table 9.9 shows that power density decreased during all conditions compared to the EO baseline. These changes are primarily over the parietal cortex. No differences were observed between the experimental conditions and their respective control conditions.

The same regression procedures described above did not produce any statistically significant results. As observed in alpha, there were a number of electrodes which suggested that MRT predicted the change from EO to EN or IR (i.e. a significant t value), but the overall F ratio was non significant , so they were not reported. Given the observation that baseline alpha was related to MRT performance, Pearson correlations were performed between MRT, EO, EN and IR. The only statistically significant correlations were between MRT and EO, again primarily over the right posterior hemisphere: Pz (r = 0.49, p = 0.03); P4 (r = 0.51, p =0.03); O2 (r = 0.48, p =0.04); P4O2 (r = 0.5, p 0.03). The relationship between beta 1 activity at P4 recorded during the baseline and MRT performance can be seen in Figure 9.11.

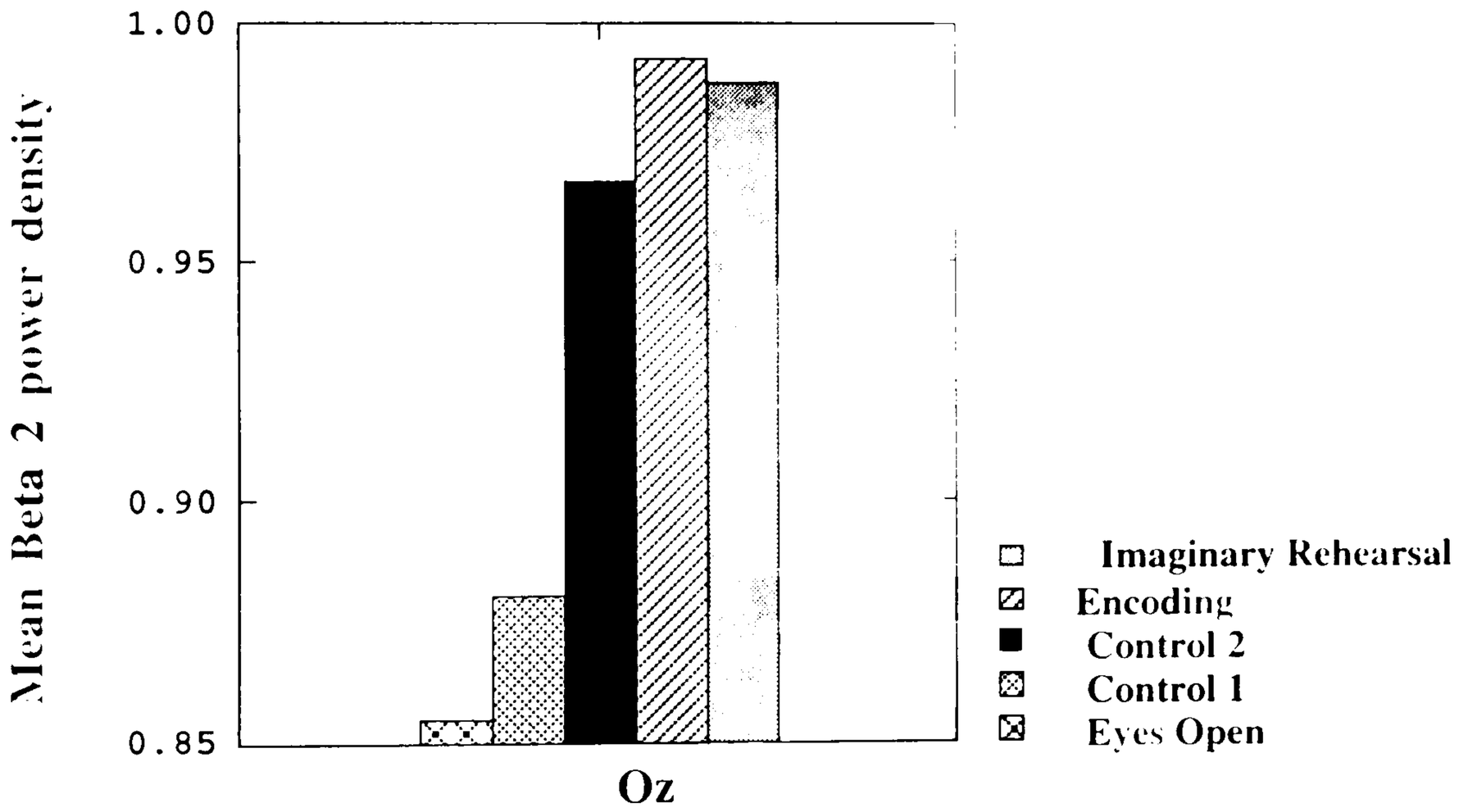
Figure 9.11 Correlation of beta 1 Power density at P4O2 with MRT performance



Beta 2

The means and standard deviations of power density at each electrode in the beta 2 frequency band during each conditions of the experiment are presented in Appendix A. Table A9.3. This table shows that power density is lower than that observed in alpha and beta 1. It also shows that there appears to very little difference in power density between the different conditions over the posterior region. Furthermore, in contrast to alpha and beta 1, power density appears *lower* during EO compared to the other conditions particularly over the occipital area. See Figure 9.12

Figure 9.12 Beta 2 Power density recorded during all five conditions

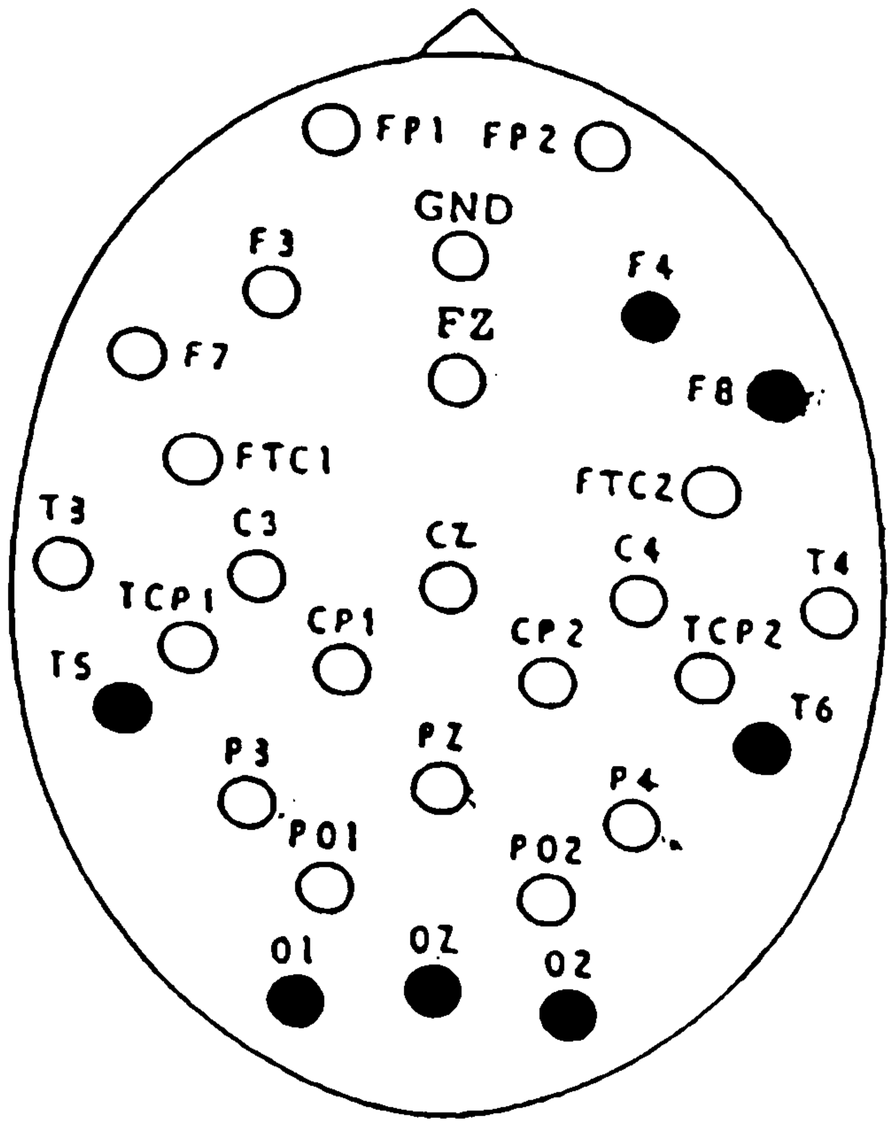


The above figure demonstrates that in contrast to alpha and beta 1, power density in the beta 2 frequency band is lower during EO compared to the other experimental conditions. MANOVA indicated a *non significant* effect of experimental condition [F (4,72) = 0.51, $p > 0.05$]. Repeated measures ANOVAs were performed on data recorded at each electrode during each type of condition (see Chapter 5). Trends in the data were found at a number of different sites, the details of which are summarised in Table 9.10. Those electrodes which showed significant differences are shown in Figure 9.13.

Table 9.10 Electrodes at which condition effects were observed in beta 2

Electrode	d.f.	F -ratio	p
F4	4,72	4.52	0.01
F8	4,72	3.43	0.025
T5	4,72	3.28	0.03
T6	4,72	3.62	0.02
O1	4,72	4.89	0.005
Oz	4,72	4.75	0.006
O2	4,72	4.24	0.009
P3O1	4,72	5.06	0.009
P4O2	4,72	3.65	0.03

Figure 9.13 Figure showing locations of main condition effects in beta 2



A summary of post hoc analysis is presented in Table 9.11

Table 9.11a Electrodes demonstrating a change in beta 2 from the Eyes Open baseline to the Control 2 condition

Electrode	Condition	p (Tukey)
F8	EO* - CON 2	0.01
O1	EO* - CON 2	0.034

Table 9.11b Electrodes demonstrating a change in beta 2 from the Eyes Open baseline to the Encoding condition

Electrode	Condition	p (Tukey)
F4	EO* - EN	0.001
F8	EO* - EN	0.024
T5	EO* - EN	0.01
O1	EO* - EN	0.003
Oz	EO* - EN	0.008
O2	EO* - EN	0.01
P3O1	EO* - EN	0.014
P4O2	EO* - EN	0.017

Table 9.11c Electrodes demonstrating a change in beta 2 from the Eyes Open baseline to the Imaginary Rehearsal condition

Electrode	Condition	p (Tukey)
O1	EO* - IR	0.01
Oz	EO* - IR	0.02

* indicates lower power density during that condition

EO = Eyes Open Condition
CON 1 = Control 1
CON 2 = Control 2
EN = Encoding IR = Imaginary Rehearsal

In summary Table 9.11 shows that there is higher power density during the CON 2, EN and IR conditions compared to the EO baseline at a number of different electrodes, but particularly over the occipital cortex. In particular power density during the encoding condition was higher than that recorded during EO. No difference was found between the imaginary rehearsal condition and its control condition.

Regression procedures showed that none of the measures of imagery ability predicted a change from the EO to either EN or MR. Pearson correlations showed that there were no significant relationships between any of the measures.

To examine whether there were any significant differences between power density recorded during the first 3 trials and last 3 trials in the imaginary rehearsal conditions, a series of t -tests were performed on the data. Analysis showed that there was no difference between power density recorded during the first 3 and last 3 trials of the imagery condition.

9.4 Discussion

In experiment 5 a number of predictions were tested:

Behavioural Predictions

1. It was predicted that an increase in the accuracy of recall would be observed over trials.

2. It was also predicted that imaginary rehearsal and physical rehearsal would produce similar learning curves during recall.

3. Finally it was predicted that physical and imaginary rehearsal trials would exhibit similar temporal characteristics to each other and to their corresponding recall trials.

All three predictions were supported by these data. A significant improvement in recall was observed but only up to trial number 3 in each condition, after which no further improvement was observed. These data suggest that the task was relatively easy to learn and after the first 3 attempts a ceiling effect was observed. There was no significant difference between the accuracy of recall following imaginary and physical rehearsal. Indeed the learning curves in both conditions are remarkably similar suggesting that imaginary rehearsal has a similar effect on learning as physical rehearsal. There was no difference in the time taken to physical rehearse or mentally rehearse the sequence or between the time taken to rehearse or recall the sequence.

It could be argued that the absence of a control condition does not prove that imagery *per se* is responsible for the increase in recall. Strictly speaking this is true, but it is suggested that the temporal characteristics of the different conditions provide strong evidence, albeit indirect, that subjects were engaging in imaginary rehearsal. It has been shown in previous studies that production of movement and the imagination of movement have similar temporal characteristics (Landauer, 1962; Decety, *et al.*, 1989; Decety & Michel, 1989). The results from this study support these findings and are consistent with the hypothesis that subjects used imagery during this condition the similarity in recall to physical practice being a result of this activity. Nonetheless, as a means of strengthening this position it would be advantageous to repeat the experiment and include an appropriate control condition.

Psychophysiological Predictions

1. It was predicted that power density in the alpha and beta bands over pre-frontal, posterior temporal and parieto-occipital cortex would be lower during the encoding and

imaginary rehearsal of the sequence compared to an eyes open baseline and to a number of control conditions.

The results partially supported this prediction. A reduction in alpha power density was observed primarily over posterior regions during the encoding and imaginary rehearsal of the sequence compared to the EO baseline. In the beta 2 frequency changes in power density were in the opposite direction to that predicted; there was an increase in power density over pre-frontal and posterior regions of cortex during all the other conditions compared to EO.

It is important to note that there were no differences were observed between the experimental conditions and their relevant controls though there were significant differences between the EO and the control conditions. This finding suggests that the EEG may not be sufficiently sensitive to detect task related changes in neural activity associated with a single experimental component. If EO is a valid baseline, then these results are important as they demonstrate that cortical areas known to be involved in the processing of high level motor and visuo-spatial information are active during imaginary rehearsal.

Ray and Cole (1985) suggest, the alpha frequency is an index of attention. If this hypothesis is correct, then the decrease in power density observed in all conditions, reflects an increased level of attention during these conditions. There are, however, different patterns of cortical activation in each of these conditions. In control 1 (subjects attended to the sequence on the monitor) a decrease in power density was observed over the left and central pre-frontal cortex and over temporal, parietal and occipital cortex bilaterally. During control 2 (subjects attended to the matrix on the pad) a decrease in power density was only found over the left hemisphere. These results are difficult to explain, but the variability of activation during each condition suggest that they have different attentional loads. This interpretation suggests that in Control 2, attentional

processes are related to left hemisphere processing (cf. Experiment 1) though no explanation is offered as to why this is the case in this particular condition.

During the encoding condition (subjects attended to and remembered the sequence) a decrease in alpha power density was observed over the temporal lobes perhaps reflecting the role of this region in the encoding of this information.

In the IR condition a decrease in alpha was found over both posterior hemispheres and over the central pre-frontal region. This latter finding is particularly important as the decrease in power density was found at Fz which is situated over the SMA and may well reflect the activity related to the temporal and sequential organisation of movement information during imaginary rehearsal. It has been suggested that the SMA is involved in the temporal organisation and programming of movement (Eccles, 1982; Roland *et al.*, 1980). Jeannerod (1984) suggests that the contents and characteristics of movement imagery become available for conscious inspection and manipulation when a goal plan is not transformed into action. This implies that subjects have to attend to these internal representations, so activity over the SMA could be interpreted as reflecting conscious attention to this information.

Given that posterior areas of the cortex thought to subserve visuo-spatial components of imagery are also active during this condition, in addition to the fact that imaginary and physical rehearsal had similar temporal characteristics produced similar trends in recall, then it is possible that the decrease in power density over this region reflects activity of the SMA. It is unfortunate that data collected during physical rehearsal could not be used in analysis as this would have had a direct bearing on this interpretation.

In beta 1, the decrease in power density during these conditions were more localised suggesting that alpha does reflect a generalised effect of attentional processes on the EEG even though it varies according to task demands. Changes in beta 1 were primarily over

the parietal cortex suggesting that it reflects some form of spatial processing during the different conditions. Although the control conditions are assumed to have a lower load than the experimental conditions they nonetheless have a spatial component. In Control 1 subjects attended to a sequence of particular items in different spatial locations whereas in Control 2, although instructed to look at the centre block on the pad, subjects had to change their attentional focus and observe the different blocks in sequence. Each condition has, therefore, a spatial component which is clearly reflected by this activity over the parietal lobes.

In beta 2 the observed change in power density was in the opposite direction to that predicted; there was an increase during the experimental conditions compared to the EO baseline. There were no changes in power density during Control 1 and those electrodes which reached significance in Control 2 (F8 and O1) are difficult to explain particularly given the distance between the two electrodes.

During encoding, the pre-frontal and posterior cortex was active bilaterally whereas during imaginary rehearsal the left and central occipital cortex was active. What is interesting is that power density did not only *increase* during these conditions but during IR this change was restricted to the occipital cortex, supporting the view that these areas become active during visual imagery. These data suggest that activity in beta 2 reflects processes related to movement imagery and that an increase in the level of cognitive processing is not always accompanied by a decrease in power density. These data are particularly interesting given the results of Beyer *et al.*, (1990) and Marks & Isaac (1994) who also reported an increase in absolute power during movement imagery. The localisation of activity over the occipital cortex also adds weight to the suggestion that beta 2 reflects more cognitive elements of task. Again it is could be argued that this increase in power density is a result of muscle activity but given the locus of this activity it is unlikely that muscle is responsible (cf. Chapter 8 Table 8.14).

Taken together, these changes in power density in all three frequency bands are interpreted as offering support for the involvement of both motor and visuo-spatial systems in movement imagery. although the changes in power density are also found in other conditions they are not always found at the same electrodes that were active during imaginary rehearsal. Although Ray and Cole (1985) suggest that alpha and beta 2 reflect attentional and cognitive processes respectively, it is suggested that all three frequency bands provide different information as to the processes involved in such a task.

2. It was further predicted that there would be a difference between the level of power density recorded during the first 3 trials and last 3 trials of the imagery conditions.

These predictions were not supported. There were no differences between power density recorded during the first and last 3 trials of the imagery condition

3. Finally, MRT performance, but not self assessment of imagery vividness. was expected to predict changes in EEG activity from the baseline and control conditions to the imaginary rehearsal condition, at the cortical areas referred to above.

This final prediction was supported by the data. Only MRT performance predicted task related changes in the EEG. As MRT performance improved the difference between EO and IR and also EN increased over the right posterior hemisphere. No relationship was found between the VMIQ, MIQ and changes in EEG or between these two sets of questionnaire data and MRT performance. The fact that only MRT predicted a change in power density from a baseline to an experimental condition is important as it again underlines the importance of relating task related brain activity to measures of individual differences that involve similar cognitive processes.

The relationship of MRT performance to the change in alpha activity over the right posterior cortex during both EN and IR suggests that as spatial ability increases, the same spatial representations are engaged during encoding and imaginary rehearsal. This finding is particularly interesting in the light of evidence that cells in the pre-motor cortex of primates fired when the animal was observing an experimenter making a particular movement and when the animal was preparing to make the same movement (di Pelligrino *et al.* 1992). Although the relationship reported here reflects activity over the right parietal cortex, it is important given the dense neural connections between parietal regions and motor regions of the frontal lobes (Fellerman & Van Essen, 1991) and the hypothesised role of the parietal lobe in visually guided movement (Kalaska & Crammond, 1992; Taira *et al.*, 1990). It is possible that performance on a task thought to activate motor and visuo-spatial areas of cortex (Chapter 6) reflects a mechanism similar to that reported by di Pellegrino *et al.* (1992). This relationship is also important as it is restricted to parietal cortex and supports previous reports of the relationship between individual differences in spatial ability and imagery related changes in cortical activity over the parietal lobe (cf. Chapter 6 and Charlot *et al.* (1992).

The absence of a relationship between EEG and questionnaire data shows that these measures do not involve the same processes that become active during this kind of task. It is suggested that given the limitations on the tasks that can be used in this kind of investigation, a vividness questionnaire should be developed to include items that involve similar processes to tasks used in a psychophysiological study. The correlation data showed that as MRT performance improved baseline alpha *increased*. This is contrary to the results of Experiment 3 where baseline power density decreased as MRT performance improved. This discrepancy in results highlights how variability in recording procedures affects the EEG. Interviews following Experiment 3 revealed that subjects had found it uncomfortable to keep their eyes open for two minutes under instructions to keep blinks to a minimum. In Experiment 5 it was decided to calculate the mean power density of two, one minute baselines separated by a forty second interval between the two trials. It

was reasoned that this approach would reduce discomfort and avoid the possibility that this had an effect on the EEG. It is suggested that the method adopted in the Experiment 5 is more likely to reflect a genuine baseline and that subject who perform well on the MRT have higher resting power density. However, further studies should be made in an attempt to replicate these results.

9.5 Conclusion

In conclusion, it is argued that this experiment demonstrates that imaginary rehearsal had similar effects on the learning of a sequence of movements to different positions in space. Although the task appears to have been very easy, and should be altered to increase the level of difficulty, these data together with those related to the temporal characteristics of demonstrate that subjects were using imagery in this task. A replication of the study using a control task between encoding and recall would demonstrate whether the improvement in recall following imagery was a result of the ease of the task or a result of imagery.

Changes in EEG activity over pre-frontal and parietal areas of the cortex also support the contention that subjects were actively engaged in movement imagery. Moreover, these changes suggest that the adoption of an 'internal visual' perspective during movement imagery engages motor and visuo-spatial representations. The observation that MRT performance predicted changes in activity over the right parietal cortex demonstrates the importance of relating cortical activity to measures of imagery ability that involve similar cognitive processes. It also demonstrates that more general measures of ability like the VMIQ and MIQ are not very useful in this kind of experiment. This is due to the limitations imposed on experimental design by psychophysiology rather than any weakness of the questionnaires themselves. A similar but more constrained instrument should be devised for such experiments.

Chapter 10

Conclusion

The main focus of this thesis was an examination of the cortical representations involved in dynamic imagery which, it is hypothesised, involves both motoric and visuo-spatial representations. A distinction was clearly made between two different forms of dynamic imagery, the imaginary transformation of objects and movement imagery, and an attempt was made to demonstrate how motoric and visuo-spatial representations interact during a number of different imaginary tasks. To that end, subjects' EEGs were recorded over cortical areas hypothesised to be involved in the processing of high level motoric and visuo-spatial information, during the performance of tasks that engage these different forms of imagery.

It was further hypothesised that cortical activity recorded during these tasks would vary as a function of individual differences in imagery ability. Due to the lack of consensus on the validity both of 'objective' and 'subjective' measures of imagery ability, both kinds of instrument were used in each of the five experiments comprising this thesis. This approach was adopted as it allowed an examination both of the relationship between these different measures and of their relationship with the EEG. Psychophysiology is thought to

produce objective evidence of imagery related processes in the brain, so any relationship between these data and the other measures of imagery ability might provide important evidence of the validity of these measures.

10.1 Imaginary Transformation

Experiment 1 investigated the cortical representations involved in imaginary transformations. Given the hypothesis that imaginary transformation involves both motoric and visuo-spatial representations it was predicted that there would be a decrease in alpha and beta power from baseline measure to a condition involving imaginary transformation (mental rotation test). This decrease in power was predicted to occur primarily over the parietal region of the cortex (reflecting visuo-spatial processes) but also over the pre-frontal cortex (reflecting motor processes involved in the planning and preparation of movement).

These predictions were partially supported by the data. A number of significant changes in activity were observed according to univariate analysis but multivariate procedures were found to be non-significant. Therefore, these results were used to describe trends in the data. A decrease in alpha and beta 1 power was found over the parietal cortex bilaterally and a decrease in beta 2 power was found over the right pre-frontal and right parietal cortex. These findings were interpreted as providing evidence of the role of these cortical areas in imaginary transformation and by implication suggest that this form of imagery involves visuo-spatial representations.

A significant decrease in alpha power was also found over the left pre-frontal cortex and trends towards a decrease were found in beta 1 and beta 2 over the left and right pre-frontal cortex, respectively. These results were interpreted as reflecting a combination of motor and other processes related to attention and decision making. They support the

general hypothesis and demonstrate the involvement of both motor and visuo-spatial processes in imaginary transformation.

Of particular interest was the finding that changes in alpha and beta 1 occurred over both hemispheres whereas changes in beta 2 were found only over the right hemisphere. Ray and Cole (1985) suggested that this faster frequency band reflects more cognitive elements of a task whereas the slower bands reflect attentional processes. In the light of this hypothesis, data from experiment 1 suggest that the attentional and cognitive processes involved in this form of cognitive activity may be lateralised to the left and right hemisphere respectively. Changes in alpha and beta 1 over the left pre-frontal cortex support previous evidence that this area is crucial in the performance of visuo-motor tasks requiring mental transformation (Kim *et al.*, 1984). Changes in beta 2 power demonstrated the central role of the right hemisphere in the transformation process.

In summary, Experiment 1 showed that both parietal and pre-frontal cortex are involved in imaginary transformations, supporting the hypothesis that this form of dynamic imagery comprises both visuo-spatial and motoric representations.

10.2 Movement Imagery

The nature of the cortical representations involved in movement imagery was investigated in experiments 2 to 5. Movement imagery has been conceptualised as activating the same processes used in the preparation for movement (Jeannerod, 1994). On the basis of evidence suggesting that cortical areas known to be involved in the planning and temporal organisation of movement (pre-frontal cortex, lateral and medial premotor cortex) are also active during movement imagery, it was hypothesised that there would be a change in EEG power recorded over these cortical areas when subjects are engaged in movement imagery.

It was also hypothesised that movement imagery engages visuo-spatial representations that may have been encoded during actual movement. Given the evidence that cortical areas known to be involved in the processing of visual information (primary visual cortex, visual association cortex) also become active during visuo-spatial imagery, it was hypothesised that there would also be a change in EEG power recorded over these cortical areas when subjects engaged in movement imagery. Furthermore, it was hypothesised that the degree of this change would be dependent upon whether an 'internal' or 'external' perspective was adopted during imagery.

In experiment 2 an attempt was made to distinguish between patterns of cortical activity recorded during movement imagery taken either from an internal or external perspective. The EEG was recorded while subjects imagined themselves and imagined someone else performing an action. It was predicted that there would be a decrease in EEG power over pre-frontal cortex during both types of imagery, although the degree of this change would be greater during internal imagery compared to external imagery reflecting the greater 'weight' of motor/kinaesthetic representations in this form of imagery. A further prediction was that there would be a decrease over parieto-occipital areas during movement imagery, an effect that would be greater during external imagery compared to internal imagery reflecting the greater 'weight' of visuo-spatial representations in this form of imagery.

Neither of these predictions was supported by the data. The failure to observe any significant change in EEG activity was explained in terms of the low cognitive demands of the items taken from the VMIQ, a problem derived from the weaknesses inherent to this kind of questionnaire. These include a lack of control over subject compliance, the arbitrary nature of the rating scale and the likelihood that subjects use different criteria in assessing the vividness of an image.

As changes in the EEG had been observed during performance of a task thought to produce objective evidence of imagery (experiment 1), but were not observed during performance of a task that produces subjective evidence of imagery (experiment 2), experiments 3 and 4 were designed to incorporate a task that had previously produced objective evidence of the effects of movement imagery on short term memory of movement.

In experiments 3 & 4, EEG was recorded while subjects performed a linear positioning task that had been adapted from Johnson (1982). On the basis of Johnson's evidence, it was predicted that self-paced overt movement and the imagination of movement half the length of a previously learned movement, interpolated between learning and recall, would result in the underestimation of the movement during recall. Given the hypothesised role of the pre-frontal cortex in movement imagery it was predicted that in comparison to a baseline, alpha and beta would be lower over these regions of cortex during the imagery condition. Furthermore, given the hypothesis of functional equivalence of overt movement and imagery of movement it was predicted that there would be comparable levels of EEG over pre-frontal cortex during these conditions.

Even though subjects in Johnson's study were instructed to imagine themselves making the movement (a perspective that has been argued to involve motor/kinaesthetic representations), it was suggested that visual feedback available during the experiment would result in the adoption of an 'internal visual' perspective during imagery. Therefore, it was likely that visuo-spatial representations would be active during this kind of imagery. To emphasise the difference between visuo-spatial and kinaesthetic representations in movement imagery, subjects received visual feedback during each of the conditions of experiment 3, whereas they were blindfold during all conditions of experiment 4. In experiment 3 it was predicted that there would be a reduction in alpha and beta over parieto-occipital areas during movement imagery, whereas in experiment 4 it was predicted that a reduction would be observed only over parietal cortex.

In experiment 3 and 4 these predictions were not supported by the data. In experiment 3 subjects overestimated rather than underestimated the movement following interpolated activity comprising either of overt movement or movement imagery. Psychophysiological data showed that there was no significant difference in the EEG recorded during the baseline and imagery conditions. Furthermore, EEG recorded over the pre-frontal cortex was significantly lower during the acquisition and recall conditions compared to the movement imagery condition. In experiments 4 overt movement interpolated between learning and recall did cause a bias in the expected direction, but this effect was not large enough to be statistically significant. Movement imagery did not produce any bias. As in experiment 3, there was no significant difference in the level of EEG recorded during the baseline and imagery conditions. Furthermore, EEG was significantly lower in the overt movement conditions compared to the movement imagery condition.

Given the findings of Johnson (1982) the results of experiments 3 & 4 were suprising, particularly with regard to the behavioural data. The main observation of Johnson's experiments, that interpolated activity causes a bias in recall, was not replicated in either study. It was suggested that procedural changes made to accommodate the psychophysiological paradigm, in particular the omission of the external timing device, may have been responsible for this failure to replicate his data. The device was omitted as it may have introduced artifact into the EEG signal but, by having subjects make self paced movements, important characteristics related to force and temporal aspects of the movement were not encoded during learning. The absence of interference effects suggest that imagery was not used in these tasks. It is perhaps not surprising then, that EEG recorded during the imagery condition was no different to that recorded during the baseline.

The results of experiments 3 & 4 demonstrate clearly the difficulties that are faced when attempting to modify behavioural tasks to suit psychophysiology. Johnson's paradigm

was chosen as it had produced clear evidence of the effect of movement imagery on performance and because it required very simple movements. Given the problem of muscle related artifact, the importance of using task related movements with few degrees of freedom cannot be over emphasised. The use of very simple movements may, however, be counter-productive. Previous demonstrations of the involvement of high level neural motor structures in movement imagery have used tasks which involve complex sequences of movements requiring considerable internal programming. The task used by Johnson involves very simple movement that requires little or no programming, so the removal of an experimental component that was crucial in the encoding of important information resulted in the task have even lower cognitive demands.

Experiment 5 investigated these same hypotheses but it incorporated a task that was considered to have a much high cognitive load. A computerised version of the Corsi blocks task was modified so that subjects would have to learn a complex sequence of movements in more than one plane. In this task subjects observed a sequence, then either physically or mentally rehearsed the sequence and finally recalled the sequence.

Behavioural predictions suggested that physical and imaginary rehearsal would have similar effects on the learning of this sequence and that both forms of interpolated activity would have similar temporal characteristics. This latter variable was included to provide an additional, albeit indirect, measure of the use of movement imagery.

Each of the behavioural predictions was supported by the data, demonstrating that imaginary rehearsal and physical rehearsal had similar effects on the learning of movement related information. In addition, both rehearsal conditions had similar temporal characteristics supporting the hypothesis that temporal information is encoded during movement imagery. These data showed that subjects were using imagery in this study and that it had a beneficial effect on performance. It was apparent that the task was

learned very quickly so caution was exercised in interpreting these data, it being suggested that a control task should be used in any replication of this experiment.

An important theoretical issue in EEG studies is the choice of the baseline. Most studies use an eyes open or eyes closed baseline but although EEG activity recorded during this condition is thought to reflect a state of rest, it is very difficult to ensure that subjects are not engaging in cognitive activity. The most influential rCBF studies demonstrating the activation of the pre-frontal, premotor and parieto-occipital cortex during movement imagery have typically used the subtraction method. The assumption of this method is that the baseline and experimental conditions differ only with respect to the processing under investigation, so in theory this approach should have provided a more accurate baseline than an eyes open condition. This experiment was designed to compare these two different baselines.

Psychophysiological predictions stated that there would be reduction in alpha and beta bands over pre-frontal, posterior temporal and parieto-occipital cortex during both the encoding and the imaginary rehearsal of a sequence compared both to an eyes open baseline and to relevant control conditions. It was also suggested that as learning progressed a more accurate and vivid image would be generated. It was predicted that this would be indexed by lower alpha and beta during the last 3 trials of the imaginary rehearsal condition compared to the first 3 trials.

These predictions received partial support. The general hypothesis of the involvement of motoric and visuo-spatial representations of movement imagery was supported by the data. During imaginary rehearsal a decrease in alpha was observed over the pre-frontal and occipito-parietal cortex suggesting motoric and visuo-spatial representations were active during this condition. A decrease in beta 1 was observed over the parietal cortex reflecting the operation of spatial processes during this type of movement imagery. Interestingly there was an *increase* in beta 2 over the left and central occipital lobe during

imagery, suggesting that an increase in cortical activation is not always accompanied by a decrease in power density. These changes in beta 2 provide strong evidence of the activation of the occipital areas during movement imagery, supporting the contention that movement imagery involves visual representations.

Changes in all three frequency bands were interpreted as showing that both motor and visuo-spatial representations are involved in movement imagery, it being suggested that each frequency band provides distinct information of the representations involved in movement imagery: alpha decreased over pre-frontal and posterior cortex, beta 1 decreased over parietal cortex and beta 2 *increased* over occipital cortex. Although changes in alpha and beta were observed in other conditions they were not always found at those electrodes that reflected changes in cortical activity during imaginary rehearsal.

There was no difference between the EEG recorded during the first 3 and last 3 trials of the imaginary rehearsal conditions. More importantly, no differences were observed between the experimental conditions and their relevant control conditions suggesting that, due to the EEG's lack of sensitivity, the subtractive method may have serious limitations for electrophysiological studies of this kind.

It was concluded from behavioural and psychophysiological data that movement imagery engages motor and visuo-spatial representations and has a positive effect on performance.

10.3 Individual Differences

Experiments 1 & 2 were conducted at the University of Warwick, whereas experiments 2 to 5 were conducted at the DRA, Centre for Human Sciences, Farnborough. The difference in the size of subject population at these two establishments has important implications for the design used in the different experiments. Given the large population available at Warwick, 'good' and 'poor' imagers were pre-selected on the basis of their

VMIQ score thus enabling the use of a factorial design in experiments 1 & 2. A much smaller population was available at Farnborough, so subjects were not pre-selected according to their imagery ability. The distributions of individual differences data were found to be approximately normal so these measures were treated as continuous variables.

In experiment 1 subjects were classified as good and poor imagers on the basis of both their VMIQ score and their MRT performance recorded during the experiment. It was predicted that there would be a relationship between the VMIQ and the MRT. It was also expected that good and poor imagers, classified according to each of these measures, would exhibit differences in the EEG recorded over pre-frontal and parieto-occipital areas.

No relationship was found between the MRT performance and the VMIQ vividness score, consistent with the view that although both claim to measure dynamic imagery, they probably reflect different processes. No difference was found in EEG activity between subjects classified as good and poor imagers according to the VMIQ but there were differences when subjects were classified according to MRT performance. The most important result showed that alpha power in the good MRT group decreased over parietal cortex during MRT. This suggests that people with high levels of spatial ability may have more focal activation during spatial performance consistent with a more dedicated strategy involving the parietal areas. The observation that task related changes were found *only* in subjects classified according to objective performance was interpreted as showing that this type of instrument provides a more accurate assessment of imagery ability.

The same subjects used in this experiment participated in experiment 2. A difference in the EEG was expected between good and poor imagers. When classified according to their VMIQ score, the good imagery group showed a trend towards a higher level of alpha power in both pre-frontal and parieto-occipital regions bilaterally. The good

imagery group also had a significantly higher level of beta 2 over the left pre-frontal region. When classified according to MRT performance trends in the data showed that good imagers had higher alpha over the pre-frontal cortex bilaterally, and over the left and central parieto-occipital cortex. The good MRT group also had higher beta 1 and beta 2 over the same occipito-parietal areas. However, no condition effect or interaction was observed in either alpha or beta.

The failure to observe any interactions in Experiment 2 was explained by the low cognitive demands of the task and the questionable validity of the VMIQ. One possible weakness of the VMIQ is the lack of control of subjects' experience in making different movements. In the following 3 experiments the MIQ was used in addition to the VMIQ as it controls for subjects' experience, requiring subjects first to make a particular movement and then generate and rate visual and kinaesthetic images.

In experiments 3 and 4, given the spatial nature of the linear positioning task and the MRT, it was predicted that there would be a relationship between these two performance measures. It was also predicted that if experience was an important variable in the assessment of the vividness of movement images, then the MIQ would exhibit a stronger relationship than the VMIQ to performance on the linear positioning task, but no relationship would be found between the MIQ and the VMIQ. Given the results of experiment 1, no relationship was expected between MRT performance and the VMIQ and MIQ scores, though MRT performance was expected to be related to subjects' EEG.

In experiments 3 & 4, no relationship was observed between performance on the linear positioning task and any of the 3 measures used to assess imagery ability. As behavioural data suggested that subjects were not using imagery, these findings are perhaps not suprising. In experiment 3 a significant relationship *was* observed between the two questionnaires suggesting that experience does not confound subjects imagery ability as assessed by the VMIQ. However, no relationship was found between these two

questionnaires in experiments 4. The MIQ, VMIQ and MRT performance were found to be unrelated in both experiment 3 & 4. MRT performance in experiment 3 was found to be related to the EEG; those subjects who performed well on the MRT had lower levels of baseline alpha. However, this relationship was not observed in experiment 4. No relationship was observed between the questionnaire data and EEG power.

These results showed that tests that provide an objective measure of imagery may provide a more accurate index of ability than subjective questionnaires. It was also suggested that the failure to observe any relationship between performance of a movement task and the questionnaires may be a result of different processes being involved in the different measures. Both questionnaires require the imagination of a number of different kinds of movement often involving whole body movement, whereas those tasks used in psychophysiological experiments are very simple, often involving a single limb and having a large spatial component. It is possible that although these questionnaires have some practical use, particularly in applied settings, because of their generality they may be of limited use in psychophysiological experiments.

In experiment 5 it was hypothesised that only MRT performance would predict EEG activity. The VMIQ and the MIQ were not expected to be related to EEG activity or to MRT performance. These predictions were supported by the data; those subjects who demonstrated good MRT performance exhibited a greater decrease in alpha over the right parietal cortex during the encoding and imagery conditions. This finding was interpreted as supporting previous evidence of focal activation in subjects with good imagery ability. No relationship was observed between the VMIQ, MIQ and MRT performance. The failure to observe any relationship between the two questionnaires replicated findings from experiment 4 but differed to those reported in experiment 3. This suggests that one or both of these measures have weak reliability. The VMIQ has been reported to have high reliability (Isaac *et al.* ;1986), though the reliability of the MIQ has been questioned (cf. Isaac and Marks, 1994). It is likely then that the MIQ is the weaker of the two

instruments. Furthermore, no relationship was observed between either questionnaire and subjects EEG. These data showed that different types of cognitive representations are involved in the imagery task and the vividness questionnaires.

10.4 Summary

Three main questions were addressed in this thesis:

1. Does dynamic imagery involve both motor and visuo-spatial representations?

2. Does the electroencephalogram (EEG) provide objective evidence of these representations at the cortical level of the brain?

3. Are subjective and objective measures of imagery ability related to one another, and do they predict imagery related changes in cortical activity?

In response to the first question, it is argued that although there were some disappointing results, there is sufficient evidence to support the contention that dynamic imagery involves both motoric and visuo-spatial representations. Results from experiment 1 were interpreted as showing that imaginary transformations involve both motoric and visuo-spatial representations. Results from experiment 5 are interpreted as showing that movement imagery also involves both types of representation.

In response to question 2, it is suggested that the EEG does provide evidence of the involvement of motor and visuo-spatial representations in dynamic imagery. However, it does have serious limitations. The EEG was used primarily because it is non-invasive and allows greater flexibility in experimental design than other brain imaging techniques. It was stressed that the problems of artifact resulting from EMG activity and other non-biological sources presents major methodological difficulties to experimental design. For

this reason, tasks are often very simple and only involve the use of a single limb. It was also stressed that the although the task involves simple movements, it must be sufficiently complex to produce observable changes in the EEG during movement imagery.

The importance of these issues was seen in experiments 3 and 4. The design of the original experiment was altered to reduce the possibility of artifact being introduced into the signal by an external source (timing mechanism). This resulted in the removal of an important cognitive component and a decrease in the cognitive load of the task. In experiment 5 an increase in task complexity resulted in an increase of EMG activity, preventing a direct comparison of EEG recorded during movement imagery and overt movement.

The validity of an accurate baseline in EEG is also a major theoretical issue. Most studies use 'eyes open' or 'eyes closed' as it is assumed that subjects do not engage in any cognitive activity during this condition. There is no guarantee that this assumption is upheld and so in experiment 5 it was decided to compare this approach with a baseline derived from the subtractive method. Used widely in PET studies, this approach assumes that a control and an experimental task differ only with respect to a single set of processes; any significant difference in blood flow during the two conditions is assumed to reflect these processes.

No significant differences were observed between the experimental conditions and their relative controls. It is possible that the EEG is insufficiently sensitive to detect such subtle changes in activity, but one can not reach this conclusion on the basis of a single experiment. In comparison to an eyes open baseline, a significant decrease in alpha and beta was observed during both the control and experimental conditions. Thus, it is argued that these changes during the imagery condition reflect a number of processes related to attention and cognition.

In response to question 3 it is argued that the objective and subjective measures used in these experiments are not related to one another, presumably because they involve *different* dynamic imagery processes. A test which produced objective evidence of imagery (MRT) appears to be a more sensitive than vividness questionnaires to imagery related changes in the EEG. In experiment 1 subjects classified as good imagers according to their MRT score exhibited a decrease during MRT performance. In experiment 5 subjects who performed well on the MRT showed a significant decrease in alpha during the movement imagery task. Although this experiment involved movement imagery, the high spatial component of the tasks makes it likely that MRT and this task involve similar processes.

10.5 Future Directions

Although the EEG presents serious difficulties in an investigation of dynamic imagery, it is still regarded as providing a useful index of cortical activation. Given that problems of poor temporal and spatial resolution inherent to neuro-imaging techniques have been partially overcome by recent advances in image co-registration, it is suggested that future research should use EEG in tandem with other techniques such as PET and FMRI. However, different approaches should be used to investigate the two forms of dynamic imagery since they are poorly correlated.

10.5.1 Imaginary Transformation

Results from experiment 1 were interpreted as providing additional support for the contention that mental rotation involves motoric and visuo-spatial representations. It was argued that because of the poor temporal resolution of the EEG (2.56 secs) makes it difficult to correlate changes in the EEG with the specific processes involved in this task. The ERP paradigm has superior temporal resolution to the EEG and research using this approach has been interpreted as showing that the parietal cortex is the locus of the

transformation process (Peronnet and Farah, 1988). However, this study examined very few electrodes (they did not examine pre-frontal electrodes) and so the spatial resolution was very poor. Charlot *et al.* (1990) also showed an increase in parietal activity during MRT, but as discussed in Chapter 5, this method has very poor temporal resolution.

One approach to achieving a greater understanding of the role of motor and visuo-spatial processes would be to use the ERP paradigm while subjects performed the Shepard and Metzler task. This task has the advantage over the version of Vandenberg and Kuse as it provides information of the time taken to rotate an image. Modern EEG technology uses up to 128 electrodes which provides much greater spatial resolution than achieved in previous studies and so it would be able to provide both very high temporal resolution and relatively high spatial resolution. Replicating the study using the ^{15}O PET technique and then co-registering each image onto a template MRI image, would allow precision mapping of rapid changes in cortical activity that occur over pre-frontal and parieto-occipital areas during the mental rotation process. Of course one would still be confronted with problems of inter-subject averaging of images and the relatively crude statistical procedures associated with these methods. However, it is likely that such an approach would provide more detailed information of the role of motoric and visuo-spatial representations in imagery transformation than is currently available.

10.5.2 Movement Imagery

It is suggested that further attempts should be made to develop tasks that lend themselves to the questions addressed in this thesis. Although some of these experiments have been disappointing, nonetheless they have provided important information for the development of future studies. For example, the design of experiment 5 was an attempt to overcome the limitations thought to exist in the previous experiments and although some of the predictions were not supported by the data, the results were regarded as being very encouraging. Future work should build on these findings and continue to develop tasks which produce observable changes in cortical activity during movement imagery. Of

course they will probably involve very simple movements and at the present time it is difficult to see a way around this problem given the limitations of contemporary neuro-imaging techniques.

10.5.3 Individual Differences

The question of how best to assess individual differences in imagery ability and its relationship to cortical activity is still a matter of debate. On the basis of these results it is suggested that a vividness questionnaire should be developed that has direct relevance to the kinds of task that are used in psychophysiological experiments. Most tasks have a very high spatial component whereas most current questionnaires examine a wide range of movements. Thus, it is important that items in an vividness questionnaire should be more constrained and involve similar processes to those used in the movement task. This does not mean that the questionnaire should contains less items, only that it comprises items requiring the imagination of movements of limbs to different points in space and other similar movements.

It is also suggested that individual differences related to attention should also be investigated as this may also be an important variable in imagery ability. The distinction would have to be made of course between attending to internal and external events. What is meant by attention to internal events is analogous to the meditative state: some forms of meditation involve focused attention on an internal image, the aim being to reduce the constant stream of thought experienced by the conscious individual. With training, the level of attention achieved by the individual increases, thereby reducing interference from these thoughts. Of course it is likely that providing objective evidence of this increase in attention to internal events would be very difficult, but it is suggested that introspective report may provide useful information of attention span. The measurement of attention to external events is relatively easy and could adopt paradigms used by Posner and his

associates. This would provide a simple albeit crude index of how attention to external events is related to a imagery ability.

Finally, it is suggested that much greater emphasis should be placed on developing formal instructions and training procedures for subjects to improve their imagery ability. It is assumed that subjects understand what is meant when they are instructed to image particular movements, but it is possible that some information contained in an image has greater relevance with regard to improving motor performance. Subjects should be able to attend to the crucial elements of a task, so formal instruction related to these issues will improve imagery performance and in turn improve physical performance. Individual differences in attention will of course provide important information about those subjects likely to benefit from these instructions.

References

Adams, J. A. & Dijkstra, S. J. (1966) Short term memory for motor responses. *Journal of Experimental Psychology*, **71**, 314-318.

Adams, L., Guz, A., Innes, J.A. & Murphy, K. (1987) The early circulatory and ventilatory response to voluntary and electrically induced exercise in man. *Journal of Physiology*, **383**, 19-30.

Allen, G. I. & Tsukahara, N. (1974) Cerebrocerebellar communication systems. *Physiological Review*, **54**, 957-1006.

Ammons, R. B. (1958) Le Mouvement. In G. H. Steward & J. P. Steward (Eds) *Current Psychological Issues*. NY: Holt.

Anderson, J. R. (1978) Arguments concerning representations for mental imagery. *Psychological Review*, **85**, 249-277.

Andino, F. L. G., Marqui, R. D. P., Sosa, P. A. V., Lirio, M. B., Machado, C., Diaz, G., Rodriguez, P. F. & Torrez, C. C. (1990) Brain electrical field measurements unaffected by linked earlobes reference. *Electroencephalography and Clinical Neurophysiology*, **75**, 155-160.

Annett, J. & Smith, R. (1988) Motor imagery in Parkinson's Disease. In C. Cornoldi (Ed) *Pre-proceedings of the Second International Workshop on Imagery and Cognition, Padua.*

Annett, J. (1986) On knowing how to do things. *Experimental Brain Research*, **15**, 187-200.

Annett, J. (1988) Imagery and skill acquisition. In M. Denis, J. Englekamp & J. T. E. Richardson (Eds)*Cognitive and Neuropsychological Approaches to Mental Imagery.* Martinus Nijhoff, Dordrecht.

Annett, J. (1990) Relations between verbal and gestural explanations. In G. E. Hammond (Ed) *Cerebral Control of Speech and Limb Movements*. North Holland, Amsterdam.

Annett, J. (1995) Motor imagery: Perception or Action ? *Neuropsychologia.*, **33**, 1395-1417.

Baddeley, A. D. & Lieberman, K. (1980) Spatial working memory. In R. Nickerson (Ed) *Attention and Performance VIII*, pp. 521-539. Hillsdale, N. J.: Erlbaum

Baddeley, A. D. (1986) *Working Memory*. Oxford: Clarendon Press.

Baddeley, A. D., Grant, S., Wight, E. & Thomson, N. (1975) Imagery and visual working memory. In P. M. A. Rabbitt & S. Dornic (Eds) *Attention and Performance V*, pp. 205-217. London: Academic Press.

Barrett, J. & Ehrichman, H (1982) Bilateral hemispheric alpha activity during visual imagery. *Neuropsychologia*, **20**, 703-708.

Barrett, P. E. (1956) The use of the EEG in the study of imagery. *British Journal of Psychology*, **47**, 101-114.

Barrett, P. E. (1956) The use of the EEG in the study of imagery. *British Journal of Psychology*, **47**, 101-114.

Beauvios, M. F. & Saillant, B. (1985) Optic aphasia for colours and colour agnosia: a distinction between visual and visuo-verbal impairments in the processing of colours. *Cognitive Neuropsychology*, **2**, 1-48.

Behrmann, M., Winocur, G. & Moscovitch, M (1992) Dissociations between mental imagery and object recognition in a brain-damaged patient. *Nature*, **359**, 636-637.

Beisteiner, R., Hollinger, P., Lindinger, G., Lang, W. & Berthoz, A. (1995) Mental representations of movements. Brain potentials associated with imagination of hand movements. *Electroencephalography and Clinical Neurophysiology*, **96**, 183-193.

Benecke, R., Rothwell, J. C. Dick, J. P. R. Day, B. L. & Marsden, C. D. (1987) Disturbance of sequential movements in patients with Parkinson's Disease. *Brain*, **110**, 361-739.

Berger, H. (1929) Uber das Elektrenkephalogramm des Menschen. Translated and reprinted in Pierre Gloor (1969) Hans Berger on the electroencephalogram of

man. *Electroencephalography and Clinical Neurophysiology*, **(Supp 28)**, Amsterdam: Elsevier.

Berger, G. H. & Gaunitz, S. C. (1979) Self-rated imagery and encoding strategies in visual imagery. *British Journal Of Psychology*, **70**, 21-24.

Betts, G. H. (1909) The Distribution and Function of Mental Imagery. NY: Teachers College, Columbia University.

Beyer, L., Weiss, T., Hansen, E., Wolf, A. & Seidel. A. (1990) Dynamics of central nervous activation during motor imagination. *International Journal of Psychophysiology*, **9**, 75-80.

Biggins, C. A., Turetsky, B. & Fein, G. (1990) The cerebral laterality of mental image generation in normal subjects. *Psychophysiology*, **27**, 57-67.

Bisiach, B. & Luzzatti, C. (1978) Unilateral neglect of representational space. Cortex **14**, 129-133.

Breitling, D., Guenther, W. & Rondot, P. (1986) Motor responses measured by Brain Electrical Activity Mapping. *Behavioural Neuroscience*, **100**, 1, 104-116.

Brooks, L. R. (1967) The suppression of visualisation by reading. *Quarterly Journal of Experimental Psychology*, **19**, 289-299.

Brooks, V. B. (1986) *The Neural Basis of Motor Control*. Oxford: Oxford University Press.

Brown, B. B. (1966) Specificity of EEG photic flicker responses to color as related to visual imagery ability. *Psychophysiology*, **2**, 197-207.

Brown, G. D. A., Britain, A. A., Elvevag, B. & Mitchell, I. J. (1994) A computational approach to fronto-striatal dysfunction in Schizophrenia and Parkinson's disease. In M. Oaksford & G. D. A. Brown (Eds) *Neurodynamics and Psychology*. Academic Press. London.

Butters, N., Barton, M. & Brody, B. (1970) Role of the right parietal lobe in the mediation of cross-modal associations and reversible operations in space. *Cortex*, **6**, 174-190.

Campos, A. & Perez, M. J. (1988) Vividness of movement questionnaire: relation with other measures of mental imagery. *Perceptual and Motor Skills*, **67**, 607-610.

Charcot & Bernard (1883) Un cas de suppression brusque et isolée de la vision mentale des signeset des objets (formes et couleurs). *Progrés Médical*, 568-71.

Charlot, V., Tzourio, N., Zilbovicius, M., Mazoyer, M. & Denis, M. (1992) Different mental imagery abilities result in different regional cerebral blood flow activation patterns during cognitive tasks. *Neuropsychologia*, **30**, 6, 565-680.

Chater, P. (1995) Personal Communication.

Cochran, E. L., Pick, A. D. & Pick, H. L. Jr (1983) Task-specific strategies of mental 'rotation' of facial representations. *Memory and Cognition*, **11**, 41-8.

Cohen, B. H. & Saslona, M. (1990) The advantage of being an habitual visualiser. *Journal of Mental Imagery*, **14**, 101-112.

Colebatch, J. G., Deiber, M. P., Passingham, R. E., Friston, K. J. & Frakowiak, R. S.(1991) Regional cerebral blood flow during voluntary arm and hand movements in human subjects. *Journal of Neurophysiology*, **65**, 1392-1401.

Cooper, L. A. & Shepard, R. N. (1973) Chronometric studies of the rotation of mental images. In W. G. Chase (ed) Visual Information Processing, New York: Academic Press.

Cooper, L. A. (1976) Demonstration of a mental analog of an external rotation. *Perception and Pyschophysics*, **19**, 296-302.

Cooper, L. A. (1975) Mental rotation of random two-dimensional shapes. *Cognitive Psychology*. **7**, 20-43.

Coppola, R. (1990) Topographic mapping of multilead data. In J. W. Rohrbaugh, R. Johnson & R. Parasuraman (Eds), *Event Related Brain Potentials* England: Oxford University Press.

Corballis, M. C. & Sergent, J. (1988) Imagery in a commissurotimised patient. *Neuropsychologia*, **26**, 13-26.

Corballis, M. C. & McLaren, r. (1982) Interactions between perceived and imagined rotation. *Journal of Experimental psychology: Human Perception and Performance*, **8**, 215-224.

Cronk, J. M. (1967) *The effect of physical practice, mental practice, and physical-mental practice on the development of arm strength*. Unpublished doctoral dissertation, Florida State University.

Darrow, C. W. (1957) Electroencephalographic "blocking" and "adaption." *Science*, **126**, 74-75.

Davidson, R. J. & Schwartz, G. E. (1977) Brain mechanisms subserving self-generated imagery: electrophysiological specificity and patterning. Psychophysiology , **14**, 598-601.

Davidson, R. J., Chapman, J. P., Chapman, L. J. & Henriques, J. B. (1990) Asymmetrical brain electrical activity discriminates between psychometrically-matched verbal and spatial cognitive tasks. *Psychophysiology*, **27**, 528-543.

De Renzi, E. & Faglioni, P. (1967) The relationship between visuo-spatial impairment and constructional apraxia. *Cortex*, **3**, 327-342.

De Renzi, E. & Nichelli, P. (1975) Verbal and non verbal short term memory impairment following hemispheric damage. *Cortex*, **11**, 341-354.

De Renzi, E. (1978) Hemispheric asymmetry as evidenced by spatial disorders. In M. Kinsbourne (Ed.) *Asymmetrical Function of the Human Brain*. New York: Academic Press.

Dean, G. & Morris, P. E. (1991) Imagery and spatial ability: when introspective reports predict performance. In R. H. Logie & M. Denis (Eds) *Mental Images and Human Cognition*.. Elsevier .

Decety, J. & Boisson, D. (1990) Effect of brain and spinal cord injuries on motor imagery. *European Archives of Psychiatry and Clinical Neuroscience*, **240**, 39-43.

Decety, J. & Ingvar, D. H. (1990) Brain structures participating in mental simulation of motor behavior: A neuropsychological interpretation. *Acta Psychologica* **73**, 13-34.

Decety, J. & Michel, F. (1989) Comparative analysis of actual and mental movement times in two graphic tasks. *Brain and Cognition*, **11**, 87-97.

Decety, J., Jeanerrod, M. & Prablanc, C. (1989) The timing of mentally represented actions. *Behavioural Brain Research*, **34**. 35-42.

Decety, J., Jeanerrod, M., Germain, M. & Pastene, J. (1991) Vegetative response during imagined movement is proportional to mental effort. *Behavioural Brain Research*, **42**, 1-5.

Decety, J., Jeannerrod, M., Durozaed, D. & Baverel, G. (1993) Central activation of autonomic effectors during mental simulation of motor actions in man. *Journal of Physiology*, **461**, 549-563.

Decety, J., Perani, D., Jeannerod, M., Bettinardi, V., Tadary, B., Woods, R., Mazziotta, J. C. & Fazio, F. (1994) Mapping motor representations with positron emission tomography. *Nature*, **371**, 600-602.

Decety, J., Sjoholm, H., Ryding, E., Stenberg, G. & Ingvar, D. (1990) The cerebellum participates in cognitive activity: tomopraphic measurements of regional cerebral blood flow. *Brain Research*, **535**, 313-317.

Deecke, L. & Kornhuber, H. H. (1978) An electrical sign of participation of the mesial "supplementary" motor cortex in human voluntary movements. *Brain Research*, **159**, 473-476.

Deecke, L., Kornhuber, H. H., Lang, W., Lang, M. & Schreiber, H. (1985) Timing functions of the frontal cortex in sequential motor and learning tasks. *Human Neurobiology*, **4,** 143-154.

Deiber, M. P., Passingham, R. E., Colebatch, J. G., Friston, K. J., Nixon, P. D. & Frackowiak, R. S. J. (1991) Cortical areas and the selection of movement : a study with positron emission tomography. *Experimental Brain Research*, **84**, 393-402.

Deutsch, G., Bourbon, W. T., Papanicolaou, A. C. & Eisenberg, H. M. (1988) Visuospatial tasks compared via activation of regional cerebral flow. *Neuropsychologia*, **26**, 3, 445-452.

Di Vesta, F. J. Ingersoll, G. & Sunshine, P. (1971) A factor analysis of imagery tests. *Journal of Verbal learning and Verbal behavior* , **10**. 471-479.

di Pellegrino, G., Fadiga, L., Fogassi, L., Gallese, V. & Rizzolati. G. (1992) Understanding motor events: a neuropsychological study. *Experimental Brain Research*, **91**, 176-180.

Dittuno, P. L. & Mann, V. A. (1990) Right hemisphere specialisation for mental rotation in normals and brain damaged subjects. Cortex, **26**, 177-188.

Dominey, P., Decety, J., Broussolle, E., Chazot, G. & Jeannerod, M. (1995) Motor imagery of a lateralized sequential task is asymmetrically slowed in hemi-parkinson's patients. *Neuropsychologia*, **33**, 727-741.

Drever, J. (1955) Some observations on the occipital alpha rhythm. *Quarterly Journal of Experimental Psychology*, **7**, 91-97.

Drever, J. (1958) Further observations on the relation between EEG and visual imagery. *American Journal of Psychology*, **71**. 270-276.

Driskell, J. E., Copper, C. & Moran, A. (1994). Does mental practice enhance performance ? *Journal of Applied Psychology*, **79**, 481-492.

Eccles, J. C. (1982) The initiation of voluntary movements by the supplementary motor area. *Archives of Psychiatry and Neurological Sciences*, **231**, 423-441.

Egstrom, G (1964) Effect of an emphasis on conceptualising techniques during early learning of a gross motor skill. *Research Quarterly*, **35**, 472-481.

Ehrlichman, H. & Barrett, J. (1983) Right Hemisphere Specialisation for Mental Imagery: A Review of the Evidence. *Brain and Cognition*, **2**, 55-76.

Ehrlichman, H. & Weiner, M. S. (1980) EEG asymmetry during covert mental activity. *Psychophysiology*, **17**, 228-235.

Epstein, M. L. (1980) The relationship of mental imagery and mental rehearsal to performance of a motor task. Journal of Sport Psychology. 2. 211-220.

Ernest, C. H. (1977) Imagery Ability and Cognition: A critical Review. *Journal of Mental Imagery*, **2**, 181-216.

Farah, M. J. & Perronet, F. (1989) Event related potentials in the study of mental imagery. *Journal of Psychophysiology* , **3**, 99-109.

Farah, M. J. (1984) The neurological basis of mental imagery: A componential analysis. *Cognition*, **18**, 245-272.

Farah, M. J. (1985) Psychophysical evidence for a shared representational medium for mental images and percepts. *Journal of Experimental Psychology. General*, **114**, 91-103.

Farah, M. J. (1988). Is Visual Imagery Really Visual? Overlooked evidence From Neuropsychology. *Psychological Review*, **95**, 3, 307-317.

Farah, M. J. (1989) The neural basis of mental imagery. *Trends in Neurosciences*, **12**, 395-399.

Farah, M. J., Hammond, K. M., Levine, D. N. & Calvanio, R. (1988a) Visual and spatial mental imagery: Dissociable systems of representation. *Cognitive Psychology* , **20**, 439-462.

Farah, M. J., Perronet, F., Gonon, M. A. & Giard, H. (1988b) Electrophysiological evidence for a shared representational medium for visual images and visual percepts. *Journal of Experimental Psychology : General*, **117**, 248-257.

Farah, M. J., Perronet, F., Weisberg, L. L. & Monheit, M. A. (1989) : Brain activity underlying mental imagery: an ERP study: Event related potentials during image generation. *Journal of Cognitive Neuroscience*, **1**, 302-316.

Farah, M. J., Soso, M. J. & Dashieff, R. M. (1992) Visual angle of the mind's eye before and after unilateral occipital lobectomy. *Journal of Experimental psychology: Human Perception and Performance*, **18**, 241-246.

Farah, M. J., Steinhauer, S. R., Lewicki, M. S., Zubin, J. & Peronnet, F. (1988d) Individual differences in vividness of mental imagery: an ERP study. *Psychophysiology* , **25**, 444-445.

Farrell, S. M. & Shepard, R. N. (1981) Shape, orientation and apparent rotational motion. *Journal of Experimental Psychology: Human Performance and Perception*, **7**, 477-486.

Fein, G., Galin, D., Yingling, C. D., Johnstone, J. & Nelson, M. A. (1984) EEG spectra in 9 -13 year-old boys are stable over 1-3 years. *Electroencephalography and Clinical Neurophysiology* , **58**,517-518.

Fellerman, D. J. & Van Essen, D. C. (1991) Distributed hierarchical processing in the primate cerebral cortex. *Cerebral Cortex*, **1**, 1-47.

Feltz, D. L. & Landers, D. M. (1983) The effects of mental practice on motor skill learning and performance: a meta-analysis. *Journal of Sport Psychology*, **5**, 25-57.

Feltz, D. L., Landers, D. M. & Becker, B. J. (1983) *A revised meta-analysis of the mental practice literature on motor learning skill*. Washington, DC: National Academy Press, Publication on Demand Program.

Finke, R. A. & Schmidt, M. J. (1977) Orientation-specific color aftereffects following imagination. *Journal of Experimental Psychology: Human Perception and Performance*, **3**, 599-606.

Finke, R. A. & Schmidt, M. J. (1978) The quantitative measure of pattern representation in images using orientation-specific color aftereffects. *Perception and Psychophysics*, **23**, 515-520.

Finke, R. A. (1979) The functional equivalence of mental images and errors of movement. *Cognitive Psychology*, **11**, 235-264.

Fischer, S. C. & Pellegrino, J. W. (1988) Hemisphere Differences of Components of Mental Rotation. *Brain and Cognition*, **7**, 1-15.

Fitts, P. M. & Posner, M. I. (1967) *Human Performance*. Belmont, CA: Brooks/Cole.

Fox, P. T., Pardo, J. V., Petersen, S. E. & Raichle, M. E. (1987) Supplementary motor and premotor responses to actual and imagined hand movements with positron emission tomopraphy. *Society for Neuroscience Abstracts*, **13**, 1433.

Fox, P. T., Fox, J. M., Raichle, M. E. & Burde, R. M. (1985) The role of the cerebral cortex in the generation of voluntary saccades: a positron emission tomography study. *Journal of Neurophysiology*, **54**, 348-369.

Frith, C. D., Friston, K., Liddle, P. F. & Frackowiak, R. S. J. (1991) Willed actions and the pre-frontal cortex in man: a study with PET. *Proceedings of the Royal Society of London, B*, **244**, 241-246.

Furst, C. J. (1976) EEG alpha asymmetry and visuospatial performance. *Nature*, **260**, 254-255.

Galton, F. (1880) Statistics and Mental Imagery. *Mind*, **5**, 301-318.

Galton, F. (1883) *Inquiries into human faculty and its development*. London: Macmillan

Gandevia, S. C. & McCloskey (1977) Changes in motor commands, as shown by changes in perceived heaviness, during partial curarization and peripheral anaesthesia in man. *Journal of Physiology*, **272**, 673-689.

Gandevia, S. C. (1982) The perception of motor commands of effort during muscular paralysis. *Brain*, **105**, 151-159.

Garneski, T. M. & Steelman, H. F. (1958) Equalising ear reference resistance in monopolar recording to eliminate artifactual temporal lobe asymmetry. *Electroencephalography and Clinical Neurophysiology*, **10**, 736-737.

Gasser, T., Bacher, P. & Steinberg, H. (1985) Test-retest reliability of spectral parameters of the EEG. *Electroencephalography and Clinical Neurophysiology* , **60**, 312-319.

Georgopoulos, A. P., Lurito, J. T., Petrides, M., Schwartz, A. B. & Massey, J. T. (1989) Mental rotation of the neuronal population vector. *Science*, **243**, 234-236.

Goldenberg, G., Podreka, I., Steiner, M., & Willmes, K. (1987) Patterns of regional cerebral blood flow related to memorising of high and low imagery words: An emission computer tomography study. *Neuropsychologia* , **25**, 641-664.

Goldenberg, G., Podreka, I., Steiner, M., Suess, E. & Deecke, L. (1989) Regional cerebral blood flow patterns in visual imagery. *Neuropsychologia* , **27**, 641-664.

Golla, F., Hutton, E. L. & Walter, W. G. (1943) The objective study of mental imagery. I. Physiological concomitants. Appendix on new method of electroencephalographic analysis. *Journal of Mental Science*, **89**, 216-223.

Gordon, R. (1949) An investigation into some of the factors that favour the formation of stereotyped images. British *Journal of Psychology*, 93, 156-167.

Goss, S., Hall, C., Buckolz, E. & Fishburne, G. (1986) Imagery ability and the acquisition and retention of movements. *Memory and Cognition*, **14**, 469-477.

Grush, R. (1994) Motor models as steps to higher cognition. *Behavioural and Brain Sciences*, **17**, 209-210.

Hale, B. D. (1982) The effects of internal and external imagery on muscular and ocular concomitants. *Journal of Sport Psychology*, **4**, 379-387.

Hall, C. R. & Pongrac, J. (1983) *Movement Imagery Questionnaire*. London, Ontario: University of Western Ontario.

Hall, C. R., Pongrac, J. & Buckolz, E. (1985) The measurement of imagery ability. *Human Movement Sciences*, **4**, 107-118.

Hall, C., Bernoties, L. & Schmidt, D. (1995) Interference effects of mental imagery on a motor task. *British Journal of Psychology*, **86**, 181-190.

Hall, C. R., Rodgers, M. W. M. & Barr, K. A. (1990) The use of imagery by athletes in selected sports. *The Sport Psychologist,* **4**, 1-10.

Harris, C. S. (1965) Perceptual adaption in inverted, reversed and displaced vision. *Psychological Review*, **72**, 419-444.

Haynes, W. O. & Moore, W. H. (1981) sentence imagery and recall: an electroencephalographic evaluation of hemispheric processing in males and females. *Cortex*, **17**, 49-62.

Hjorth, B. (1980) Source derivation simplifies topographical EEG interpretation. American Journal of EEG Technology, 121-132.

Housner, L. D. & Hoffman, S. (1978) Imagery and short term memory. In *Psychology of Sport and Motor Behavior*. In G. C. Roberts & K. M. Newell, (Eds) Human Kinetics Publ: Champaign Illinois.

Humphrey, D. R. (1983) Corticospinal systems and their control by premotor cortex, basal ganglia and cerebellum. In W. D. Willis (Ed) *The Clinical Neurosciences: Vol 5*. New York: Churchill Livingston.

Ingvar, D. H. & Philipson, L. (1977) Distribution of cerebral blood flow in the dominant hemisphere during motor ideation and motor performance. *Annals of Neurology*. **2**, 230-237.

Intons-Peterson, M. J. (1983) Imagery paradigms: how vulnerable are they to experimenters' expectations? *Journal of Experimental Psychology: Human Perception and Performance*, **9**, 394-412.

Isaac, A. R. & Marks, D. F. (1994) Individual differences in mental imagery experience: developmental changes and specialisation. *British Journal of Psychology*. **85**, 479-500.

Isaac, A. R. (1990) *The role of imagery in movement - its nature and function*. Doctoral dissertation. University of Otago.

Isaac, A., Marks, D. & Russell, D. (1986) An instrument for assessing imagery of movement: the Vividness of Movement Imagery Questionnaire (VMIQ). *Journal of Mental Imagery*, **10**, 23-30.

Ivanova, P. & Artemov, V. (1971) Changes in EEG during mental visualisation of motions. *USSR Research Institute of Physical Culture, Moscou*. 624-626.

Jackson, J. H. (1932) *Selected writings of John Hughlings Jackson*. Vol 2. J. Taylor (ed) London: Hodder & Stoughton

James, W. (1890) *Principles of Psychology*. London: Macmillan. (New edition, Dover, New York, 1950).

Jankowiak, J., Kinsbourne, M., Shalev, R. S. & Bachman, D. L. (1992) Preserved visula imagery and categorisation in a case of associative visual agnosia. *Journal of Cognitive Neuroscience*, **4**, 119-131.

Jasper, H. (1958) The ten-twenty system of the International Federation. *Electroencephalography and Clinical Neurophysiology*. 10, 370-375.

Jeannerod, M. (1994). The representing brain: Neural correlates of motor intention and imagery. *Behavioral and Brain Sciences*. **17**. 187-245.

Johnson, P. (1982) The functional equivalence of imagery and movement. *Quarterly Journal of Experimental Psychology*. **34A**, 349-365.

Jolicoeur, P. & Cavanagh, P. (1992) Mental rotation, physical rotation and surface media. *Journal of Experimental Psychology; Human Perception and Performance*, **16**: 371-384.

Jones, W. & Anuza, T. (1982) Effects of sex, handedness, stimulus and visual field on "mental rotation". *Cortex* , **18**, 501-514.

Kahn, E. M., Weiner, R. D., Brenner, P. & Coppola, R. (1988) Topographic maps of brain electrical activity - pitfalls and precautions. *Biological Psychiatry*, **23**, 628-636.

Kalaska, J. F. & Crammond, D. J. (1992) Cerebral cortical mechanisms of reaching movements. *Science*, **255**: 1517-1522.

Katznelson, R. (1981) In P. Nunez, P. *Electrical fields of the brain*. NY: Oxford University Press.

Kihlstrom, J. F., Glisky, M. L., Peterson, M. A., Harvey, E. M. & Rose, P. M. (1991) Vividness and control of mental imagery: a psychometric analysis. *Journal of Mental Imagery*, **15**, 133-142.

Kim, Y., Morrow, L., Passafiume, D. & Boller, F. (1984) Visuospatial and visuomotor abilities and locus of lesion. *Neuropsychologia*, **22**, 177-185.

Kimura, D. (1977) Acquisition of a motor skill after left hemisphere damage. *Brain*, **100**, 527-542.

Kohl, R. M. & Roenker, D. L. (1980) Bilateral transfer as a function of mental imagery. *Journal of Motor Behavior*, **12**, 197-206.

Kohl, R. M. & Roenker, D. L. (1983) Mechanism involvement during skill imagery. *Journal of Motor Behavior*, **15**, 179-190.

Kornheiser, A. (1976) Adaption to laterally displaced prisms: a review. *Psychological Bulletin*, **83**, 783-816.

Kosslyn, S. M. (1975) Information representation in visual images. Cognitive *Psychology*, **7**, 341-370.

Kosslyn, S. M. (1978) Measuring the visual angle of the mind's eye. *Cognitive Psychology*, **10**, 356-389.

Kosslyn, S. M. (1980) *Image and Mind*. Cambridge, MA: Harvard University Press.

Kosslyn, S. M. (1994) *Image and Brain: The resolution of the imagery debate*. MIT Press.

Kosslyn, S. M., Alpert, N. M., Thompson, W. L., Malijkovic, V., Weise, S. B., Chabris, C. B., Hamilton, S. E., Rauch, S. L. & Buonanno, F. S. (1993) Visual mental imagery activates topographically organised visual cortex: PET investigations. *Journal of Cognitive Neuroscience*, **5**, 263-287.

Kosslyn, S. M., Brunn, J., Cave, K. R. & Wallach, R. W. (1984) Individual differences in imagery ability : a computational analysis. *Cognition*, **18**, 195-243.

Krough, A. & Lindhard, J. (1913) The regulation of respiration and circulation during the initial stages of muscular work. *Journal of Physiology*, **47**, 112-136.

Laabs, G. J. (1973) Retention characteristics of different reproduction cues in motor short term memory. *Journal of Experimental Psychology*, **100**, 168-177.

Landauer, T. K. (1962) Rate of implicit speech. *Perceptual and Motor Skills*, **15**, 646.

Le Doux, J. E., Wilson, D. H. & Gazziniga, M. S. (1977) Manipulo-spatial aspects of cerebral lateralisation: clues to the origin of lateralisation. *Neuropsychologia*, **15**, 743-749.

Leenders, K. L., Palmer, A. J., Quinn, N., Clark, J. C., Firnau, G., Garnett, E. S. Nahmias, C., Jones, T. & Marsden, K. L. (1986) Brain dopamine metabolism in patients with parkinson's disease measured with positron emission tomography. *Journal of Neurology, Neurosurgery and Psychiatry*, **49**, 853-860.

Leiner, H. C., Leiner, A. L. & Dow, R. S. (1991) *Behavioral Brain Research*, **44**, 113-128.

Leissner, P., Lindholm, L. -E. & Peterson, I. (1970) Alpha amplitude dependence on skull-thickness as emasured by ultrasound techniques. *Electroencephalography and Clinical Neurophysiology*, **29**,392-399.

Lesevre, N. & Joseph, J. P. (1979) Modifications of the pattern evoked potential in relation to the stimulated part of the visual field (clues for the most probable

origin of each component. *Electroencephalography and Clinical Neurophysiology*, **47**, 183-203.

Levine, D. N., Warach, J. & Farah, M. J. (1985) Two visual systems in mental imagery.: dissociations of "what" and "where" in imagery disorders due to bilateral posterior cerebral lesions. *Neurology*, **35**, 1010-1018.

Lindsay, D. & Wicke, J. (1974) The electroencephalogram: autonomous electrical activity in man and animals. In R. Thompson and M. Patterson (Eds) *Bioelectric recording techniques: Part B. Electroencephalography and human brain potentials*. New York: Academic Press.

Logie, R. H. & Marchetti, C. (1991) Visuo-spatial working memory. In P. J. Hampson, D. F. Marks, and J. T. E. Richardson (Eds) *Imagery: Current Developments*. pp. 103-128, London: Routledge.

Logie, R. H. (1994) *Visuo-Spatial Working Memory*. Hillsdale: Erlbaum.

Lopes Da Silva, F. & Storm Van Leeuwen, W. (1978)The cortical alpha rhythm in dog: the depth and surface polarity of phase. In M. A. Brazier and H. Petsche (Eds) Architechtonics of Cerebral Cortex, NY: Raven Press.

Lorig, T. S. & Schwartz, G. E. (1989) Factor analysis of the EEG indicates inconsistencies in traditional frequency bands. *Journal of Psychophysiology*, **3**, 369-375.

Luria, A. R. (1973) *The Working Brain.* Penguin.

Lutzenberg, W. & Elbert, T. (1991) The linked reference issue in EEG and ERP recording. *International Journal of Psychophysiology*, **5**, 273-276.

Lynch, J. J., Paskewitz, D. A. & Orne, M. T. (1974) Intersession stability of human alpha rhythm density. Electroencephalography *and Clinical Neurophysiology*, **36**, 538-540.

MacGillivray, B. B. & Sawyers, F. J. P. (1988) A comparison of common reference, average and source derivations in mapping. In D. Samson-Dollfus, J. D. Guieu & P. Etevenon (Eds), *Statistics and topography in Quantitative EEG* (pp. 72-87). Paris: Elsevier.

Mahoney, M. J. & Avener, M. (1977) Psychology of the elite athlete: an exploratory study. *Cognitive Research and Therapy*, **1**, 135-141.

Mahoney, M. J., Gabriel, T. J. & Perkins, T. S. (1987) Psychological skills and exceptional athletic performance. *The Sport Psychologist*, **1**, 181-199.

Maier, J., Dagnelie, G., Spekreijse, H. & Van Dijk, B. W. (1987) Principle component analysis for source localisation of visual evoked potentials in man. *Vision Research*, **12**, 165-177.

Marks, D. F. & Isaac, A. R. (1995) Topographic distribution of EEG activity accompanying visual and motor imagery in vivid and non-vivid imagers. *British Journal of Psychology*, **86**, 271-282.

Marks, D. F. (1973) Visual imagery differences in the recall of pictures. *British Journal of Psychology*, **64**, 17-24.

Marks, D. F. (1977) Imagery and Consciousness: a theoretical review from an individual differences perspective. *Journal of Mental Imagery*, **2**, 275-290.

Marks, D. F., Uemara, K. Tatsuno, J. & Imamura, Y. (1985) EEG topographical analysis of imagery. In J. McGaugh (Ed) *Contemporary Psychology: Biological Processes and Theoretical issue*, pp. 211-223. Amsterdam: Elsevier.

Marmor, G. S. & Zabeck, L. A. (1976) Mental rotation by the blind: does mental rotation depend on visual imagery? *Journal of Experimental Psychology: Human Perception and Performance*, **2**, 515-521.

McBride, E. R. & Rothstein,, A. L. (1979) Mental and Physical Practice and the learning and retention of open and closed skills. *Perceptual and Motor Skills*, **49**, 359-365.

McCollough, C. (1965) Color adaptation of edge-detectors in the human visual system. *Science*, **149**, 1115-16.

McKelvie, S. J. (1994) Guidelines for judging psychometric properties of imagery questionnaires as research intruments: a quantitative proposal. *Perceptual and Motor Skills*, **79**, 1219-1231.

Meador, K. J., Loring, D. W., Bowers, D. & Heilman, K. M. (1987). Remote memory and neglect syndrome. *Neurology*, **37**, 522-526.

Mehta, Z. & Newcombe, F. (1991) A role for the left hemisphere in spatial processing. *Cortex*, **27**, 153-167.

Mehta, Z. Newcombe, F. & Damasio, H. (1987) A left hemisphere contribution to visuospatial processing. *Cortex*, **23**, 447-461.

Mehta, Z., Newcombe, F. & De Haan, E.(1992) Selective loss of imagery in a case of visual agnosia. *Neuropsychologia*, **30**, 7, 645-655.

Mel, B. W. (1991) A connectionist model may shed light on neural mechanisms for visually guided reaching. *Journal of Cognitive Neuroscience*, **3**, 273-292.

Mendoza, D. & Wichman, H. (1978) "Inner" darts: effects of mental practice on performance of dart throwing. *Perceptual and Motor Skills*, **47**, 1195-1199.

Michel, C. M., Kaufman, L. & Williamson, S. J. (1995) Duration of EEG and MEG alpha suppression increases with angle in a mental rotation task. *Journal of Cognitive Neuroscience*, **6**, 139-150.

Morgan, A. H., McDonald, P. J. & MacDonald, H. (1971) differences in bilateral alpha activity as a function of experimental task, with a note on lateral eye movements and hypnotizability. *Neuropsychologia*, **9**, 459-469.

Mundy-Castle, A. C. (1957) The EEG and mental activity. *Electroencephalography and Clinical Neurophysiology*, **9**, 643-655.

Nahmias, C., Garnett, E. S., Firnau, G. & Lang, A (1985) Striatal dopamine distribution in Parkinsonian patients during life. *Journal of Neurological Science*, **69**, 223-230.

Nunez, P. (1981) *Electrical fields of the brain*. NY: Oxford University Press.

Ochipa, C., Rapcsak, S. Z., Maher, L. M., Bowers, D., Gonzalez-Rothi, L.J. & Heilman, K. M. (1991) Selective deficit of motor imagery in Ideomotor apraxia. Journal *of Clinical and Experimental Neuropsychology*, **13**, 84.

Ornstein, R., Johnstone, J., Herron, J. & Swencionis, C. (1980) Differential right-hemisphere engagement in visuospatial tasks. *Neuropsychologia* , **18**, 49-64.

Oswald, I. (1957) The EEG, visual imagery and attention. *Quarterly Journal of Experimental Psychology*, **9**, 113-118.

Overby. L. Y. (1990) A comparison of novice and experienced dancers' imagery ability. *Journal of Mental Imagery*, **14**, 173-184.

Paivio, A. & Clark, J. M. (1991) Static vs Dynamic imagery. In C. Cornoldi & M. A. McDaniel (Eds) *Imagery and Cognition*, (pp. 221-245). New York: Springer.

Paivio, A. (1986) *Mental Representations. A dual coding approach*. Oxford: Clarendon Press.

Paivio, A. and Harshman, R. A. (1983) Factor analysis of a questionnaire on imagery and verbal habits and skills. *Canadian Journal of Psychology*, **37**, 461-483.

Parsons, L. M. (1987a) Imagined spatial transformations of one's body. *Journal of Experimental Psychology: General*, **116**, 172-191.

Parsons, L. M. (1987b) Imagined spatial transformations of one's hands and feet. *Cognitive Psychology*, **19**, 178-241.

Patrick, J. (1971) The effect of interpolated motor activities in short-term motor memory. *Journal of Motor Behavior*, **3**, 39-48.

Peronnet, F. & Farah, M. J. (1989) Mental rotation: An event related potential study with a validated mental rotation task. *Brain and Cognition* , **9,** 279-288.

Podgorny, P. & Shepard, R. N. (1978) Functional representations common to visual perception and imagination. *Journal of Experimental Psychology: Human Perception and Performance*, **4**, 21-35.

Poltrock, S. E. & Brown, P. (1984) Individual differences in imagery and spatial ability. *Intelligence*, **8**, 93-138.

Pylyshyn, Z. W. (1973) what the mind's eye tells the mind's brain: a critique of mental imagery. *Psychological Bulletin*, **80**, 1-24.

Pylyshyn, Z. W. (1981) The imagery debate: analogue media versus tacit knowledge. *Psychological Review*, **88**, 16-45.

Quinn J. G. (1991) Encoding and maintenance of information in visual working memory. In R. H. Logie & M. Denis (Eds)*Mental Images in Human Cognition*, pp. 95-104 Amsterdam: North Holland.

Quinn, J. G. & Ralston, G. E. (1986) Movement and attention in visual working memory. *Quarterly Journal of Experimental Psychology*, **38A**, 689-703.

Rao, S. M., Binder, J. R., Bandettini, P.A., Hammeke, T. A., Yetkin, F. Z., Jesmanowicz, A., Lisk, L. M., Morris, G. L., Mueller, W. M., Estkowski, L. D., Wong, E. C., Haughton, V. M. & Hyde, J. S. (1993) Functional magnetic resonance imaging of complex human movements. *Neurology,* **43**, 2311-238.

Rappelsberger, P. & Petsche, H. (1988) Probability mapping : power and coherence analysis of cognitive processes. *Brain Topography*, **1**, 46-54.

Rappelsberger, P., Krieglsteiner, S., Mayerweg, M., Petsche, H. & Pockbereger, H. (1987) Probability mapping of electroencephalogram changes: application to spatial imagination studies. *Journal of Clinical Monitoring*, **3**, 320-322.

Ratcliff, G. (1979) Spatial thought, mental rotation and the right hemisphere. *Neuropsychologia* , **17**, 49-54.

Rawlings, E. I., Rawlings, I. L., Chen, S. S. & Yilk, M. D.(1972) The facilitating effects of mental rehearsal in the acquisition of rotary pursuit tracking. *Psychonomic Science*, **26**, 71-73.

Ray, W. J. & Cole, H. W. (1985) EEG alpha activity reflects attentional demands and beta activity reflects emotional and cognitive processes. *Science*, **228**, 750-752.

Richardson, A. (1967 a) Mental practice: A review and discussion. Part I. *Research Quarterly* , **38**, 95-107.

Richardson, A. (1967 b) Mental practice: A review and discussion. Part II. *Research Quarterly* , **38**, 263-273.

Richardson, A. (1969) Mental Imagery. NY: Springer.

Riddoch, M. J. & Humphreys, G. W. (1987) A case of integrative agnosia. *Brain*, **110**, 1431-1462.

Robbins, K. I. & McAdam, D. W. (1974) Interhemipheric alpha asymmetry and imagery mode. *Brain and Language*, **1**, 189-193.

Roland, P. E. & Friberg, L. (1985) Localisation of cortical areas activated by thinking. *Journal of Neurophysiology*, **53**, 1219-1243.

Roland, P. E., Larsen, B., Lassen, N. A. & Skinhoj, E. (1980) Supplementary motor area and other cortical areas in organisation of voluntary movements in man. *Journal of Neurophysiology*, **43**, 1, 118-136.

Roland, P. E., Meyer, E., Shibasaki, T., Yamamoto, L. & Thompson, C. J. (1982) Regional cerebral blood flow changes in cortex and basal ganglia during voluntary movements in normal human volunteers. *Journal of Neurophysiology*, **48**, 467-480.

Roland, P. E. Skinhoj, E., Lassen, N. A. & Larsen, B. (1980) Different cortical areas in man in organisation of voluntary movements in extrapersonal space. *J. Neurophysiology,* **43,** 137-150.

Rosler, F. Schumacher, G. & Sojka, B. (1990) What the brain reveals when it thinks: event-related potentials during mental rotation and mental arithmetic. *The German Journal of Psychology*, **14**, 185-203.

Rosler, F., Heil, M., Bajric, J., Pauls, A., & Hennighausen, E. (1995) Patterns of cerebral activation while mental images are rotated and changed in size. *Psychophysiology*, **32**, 135-149.

Ryan, E. D. & Simons, J. (1981) Cognitive demand, imagery, and frequency of mental rehearsal as factors influencing acquisition of motor skills. *Journal of Sport Psychology*, **3**, 35-45.

Ryan, E. D. & Simons, J. (1983) What is learned in mental practice of motor skills: a test of the cognitive-motor hypothesis. *Journal of Sport Psychology*, **5**, 419-426.

Sackett, R. S. (1934) The influence of symbolic rehearsal upon the retention of a maze habit. *Journal of General Psychology*, **10**, 376-395.

Sacks, O & Wasserman, R. (1987) The case of the colour blind painter. *NY Review of Books*, 25-34.

Schmidt, R. A. (1982) *Motor Control and Learning: A Behavioral Emphasis.* Champaign, IL: Human Kinetics.

Schnider, A., Gutbrod, K. & Hess, C. W. (1995) Motion imagery in Parkinson's disease. *Brain*, **118**, 485-493.

Schutz, R. W. & Roy, E. A. (1973) Absolute error: the devil in disguise. *Journal of Motor Behaviour*, **5**, 141-153.

Seitz, R. J. & Roland, P. E. (1992) Learning of sequential finger movements in man: a combined kinematic and Positron Emission Tomography (PET) study. *European Journal of Neuroscience*, **4**, 154-165.

Sekiyama, K. (1983) Mental and physical movements of hands: kinaesthetic information preserved in representational systems. *Japanese Psychological Research*, **25**, 95-102.

Senulis, J. A. & Davidson, R. J. (1989) The effects of linking the ears on the hemispheric asymmetry of EEG. *Psychophysiology*, **26**, S54.

Sergent, J.(1990) The Neuropsychology of Visual Image Generation: Data, Method, and Theory. *Brain and Cognition*, **13**, 98-129.

Shagass, C. (1972) Electrical Activity of the Brain. In N. S. Greenfield and R. A. Sternbach (Eds) *Handbook of Psychophysiology*. NY: Holt, Rinehart & Winston.

Sheehan, P. W. (1967) A shortened version of the Betts Questionnaire upon mental imagery. *Journal of Clinical Psychology*, **23**, 386-389.

Shepard, R. N. & Metzler, J. (1971) Mental rotation of three-dimensional objects. Science , **171**, 701-703.

Shepard, R. N. (1980) *Internal representations: studies in perception imagery and cognition*. Bradford Books, Montgomery, Vermont.

Shepard, R. N. (1988) The role of transformations in spatial cognition. In J. Stiles-Davis, M. Kritchevsky and A. Bellugi (Eds) *Spatial Cognition, Brain Bases and Development.*

Short, P. L. (1953) The objective study of mental imagery. *British Journal of Psychology*, **44**, 38-51.

Shuttleworth, E. C., Syring, V. and Allen, N. (1982) Further observations on the nature of prosopagnosia. *Brain and Cognition*, **1**, 302-332.

)

Singer, J. L. & Antrobus, J. S. (1972) Day dreaming, imaginal processes and personality: a normative study. In P. W. Sheehan (Ed.) *The Function and Nature of Imagery*. NY: Academic Press.

Slatter, K. H. (1960) Alpha rhythm and mental imagery. *Electroencephalography and Clinical Neurophysiology*, **12**, 851-859.

Smith, L. E. & Harrison, J. E. (1962) Comparison of the effects of visual, motor, mental and guided practice upon speed and accuracy of performing a simple eye-hand coordination task. *Research Quarterly*, **33**, 299-230.

Smyth, M. M. & Pelky, P. L. (1992) Short-term retention of spatial information. *British Journal of Psychology*, **83,** 359-374.

Smyth, M. M. & Pendleton, L. R. (1989) Working memory for movements. *Quarterly Journal of Experimental Psychology*, **41A**, 235-250.

Smyth, M. M. & Scholey, K. A. (1992) Determining spatial span: the role of movement time and articulation rate. *Quarterly Journal of Experimental Psychology*, **45A**, 479-501.

Smyth, M. M. (1984) Memory for movements. In M. Smyth & A. M. Wing (Eds) The Psychology of Human Movement. London: Academic Press.

Smyth, M. M., Pearson, N. A. & Pendleton, L. R. (1988) Movement and Working memory: patterns and positions in space. *Quarterly Journal of Experimental Psychology*, **40A**, 497-514.

Sokolov, E. N. (1963) Higher nervous functions: the orienting reflex. *Annual Review of Physiology*, **25**, 545-580.

Spydell, J. D. & Sheer, D. E. (1982) Effect of problem solving on right and left hemisphere 40 Hertz EEG activity. *Psychophysiology*, **19**, 420-425.

Start, K. B. & Richardson. A. (1964) Imagery and mental practice. *British Journal of Educational Psychology*, **34**, 280-284.

Stebbins, R. J. (1968) A comparison of the effects of physical and mental practice in learning a motor skill. *Research Quarterly*, **39**, 728-734.

Stelmach, G. E. & Walsh, M. F. (1973) The temporal placement of interpolated movements in short-term motor memory. *Journal of Motor Behavior*, **5**, 165-173.

Stephan, K. M., Fink, G. R. Frith, C. D. & Frackowiak, R. S. J. (1993) Functional anatomy of mental representation of hand movements in healthy subjects. *International Union of Physiological Sciences (Glasgow)*. Abstract 49 7/P.

Taira, M., Mine, S., Georgopoulos, A. P., Murata, A. & Sakata, H. (1990) Parietal cortex neurons of the monkey related the visual guidance of hand movement. *Experimental Brain Research*, **83**, 29-36.

Taylor, R. (1993) Imagery: its role in mental rehearsal to improve sport performance. *A research study for the Scottish Sports Council*. Edinburgh: Scottish Sports Council.

Thatcher, R. W. & John, E. R. (1977) *Functional Neuroscience: Vol 1, Foundations of Cognitive Processes*. Hillsdale NJ: Erlbaum.

Thatcher, R. W. & Purpura, D. P. (1973) Post natal development of thalamic synaptic events underlying evoked recruiting responses and electrocortical activation. *Brain Research*, **60**, 21-34.

Tomarken, A. J., Davidson, R. J., Wheeler, R. E. & Kinney, L. (1992) Psychometric properties of resting anterior EEG asymmetry: temporal stability and internal consistency. *Psychophysiology*, **29**, 576-592.

Valentine, T. & Bruce, (1988) Mental rotation of faces. *Memory and Cognition*, **16**, 556-566.

Van Dis, H., Corner, M., Dapper, R., Hammond, G. & Kok, H. (1979) Individual differences in the human electroencephalogram during quiet wakefulness. *Electroencephalography and Clinical Neurophysiology*, 47, 87-94.

Van Petten, C. & Kutas, M. (1988) The use of event related responses in the study of brain asymmetries. *International Journal of Neuroscience*, **39**, 91-99.

Vandenberg, S. G. & Kuse, A. R. (1978) Mental rotations, a group test of three dimensional spatial visualisation. *Perceptual Motor skills* , **47**, 599-604.

Vogel, W., Broverman, D. & Klaiber, E. (1968) EEG and mental abilities. *Electroencephalography and Clinical Neurophysiology*, **24**, 166-175.

Walshe, W. D., Russell, D. G. & Imanaka, K. (1980) Memory for movement: interaction of location and distance cues and imagery ability. *Acta Psychologia*, **44**, 117-130.

Walter, R. D. & Yeager, C. L. (1956) Visual imagery and EEG changes. *Electroencephalography and Clinical Neurophysiology*, **8**.193-199.

Weimer, W. B. (1977) A conceptual framework for cognitive psychology: motor theories of the mind. In R. Shaw and J. Bransford (Eds) *Perceiving, Acting and Knowing.* Hillsdale, NJ : Erlbaum.

Welch, R. B. (1978) *Perceptual modification: adapting to altered sensory environments.* New York: Academic Press.

Wessel, K., Zeffiro, T., Lou, J-S., Toro, C. & Hallett, M. (1995) Regional cerebral blood flow during a self-paced sequential finger opposition task in patients with cerebellar degeneration. *Brain*, 118, 379-393.

White, A. & Hardy, L. (1995) Use of different imagery perspectives on the learning and performance of different motor skills. *British Journal of Psychology*, **86**, 169-180.

White, K. D., Ashton, R. & Lewis, S. (1979) Learning a complex skill: effects of mental practice, physical practice and imagery ability. *International Journal of Sport Psychology*, **10**, 71-78.

Whiting, H. T. A. and den Brinker, B. (1982) Image of the act. In J. P Das, R. F. Mulcahy & A. E. Wall (Eds) *Theory and Research in Learning Difficulties*. NY: Plenum Press.

Wiggins, D. K. (1984) The history of sport psychology in North America. In J. M. Silva and R. S. Weinberg (Eds) *Psychological Foundations of Sport* (pp. 9-22). Champaign. IL: Human Kinetics.

Wilkinson, D. A. (1971) Visual-motor control loop: a linear system? *Journal of Experimental Psychology*, **89**, 250-257.

Wrisberg, C. A. & Ragdale, M. R. (1979) Cognitive demand and Practice level: factors in the mental rehearsal of motor skills. *Journal of Human Movement Studies*. **5**. 201-208.

Yue, G. & Cole, K. J. (1992) Strength increases from the motor program: comparison of training with maximal voluntary and imagined muscle contractions. *Journal of Neurophysiology*, **67**, 1114-1123.

Zecker, S. G. (1982) Mental Practice and knowledge of results in the learning of a perceptual motor skill. *Journal of Sport Psychology*. **4**, 52-63.

Appendix A

Table A6.1 Summary of means and standard deviations of alpha power in good and poor imagers (VMIQ).

	Poor Imagers		Good Imagers	
	EO	MRT	EO	MRT
	Mean SD	Mean SD	Mean SD	Mean SD
F7	5.845 (1.71)	6.733 (1.67)	7.605 (4.09)	7.641 (3.48)
F3	7.383 (2.54)	7.448 (2.46)	9.402 (4.90)	8.773 (4.27)
FZ	7.807 (2.59)	8.053 (2.77)	9.402 (4.66)	9.058 (4.50)
F4	7.554 (2.42)	7.315 (2.64)	9.109 (4.69)	7.986 (3.60)
F8	5.763 (1.85)	6.359 (1.73)	6.960 (3.00)	7.078 (2.54)
TCP1	7.682 (3.18)	7.300 (2.90)	10.071 (5.23)	9.022 (4.39)
CP1	9.658 (5.52)	8.738 (3.93)	12.121 (7.78)	10.786 (6.22)
CP2	8.699 (4.88)	7.808 (3.50)	10.561 (6.55)	9.347 (4.88)
TCP2	7.023 (3.31)	6.346 (2.61)	8.852 (4.11)	7.817 (3.71)
P3	9.195 (4.82)	8.223 (3.23)	10.038 (4.01)	7.962 (2.99)
PZ	9.978 (6.05)	9.059 (4.08)	12.542 (6.70)	11.119 (6.35)
P4	9.801 (5.42)	8.378 (3.49)	11.533 (5.79)	9.397 (5.17)
PO1	7.910 (3.60)	7.852 (2.70)	11.663 (6.44)	10.278 (5.52)
PO2	9.533 (4.41)	8.659 (2.66)	12.262 (6.15)	10.741 (6.46)

EO = Eyes Open Baseline

MRT = Mental Rotation Test

Table A6.2 Summary of means and standard deviations of beta 1 power in good and poor imagers (VMIQ).

	Poor Imagers		Good Imagers	
	EO	MRT	EO	MRT
	Mean SD	Mean SD	Mean SD	Mean SD
F7	4.905 (1.03)	4.897 (1.15)	5.287 (1.19)	4.878 (0.85)
F3	5.605 (1.31)	5.302 (1.51)	6.188 (2.17)	5.625 (1.49)
FZ	4.983 (1.33)	5.001 (1.47)	5.484 (1.96)	5.121 (1.48)
F4	5.339 (1.24)	5.137 (1.66)	6.033 (2.24)	5.156 (1.37)
F8	4.673 (1.33)	4.499 (1.02)	4.670 (1.25)	4.506 (0.92)
TCP1	6.217 (1.86)	5.438 (1.44)	5.817 (1.93)	5.493 (1.72)
CP1	6.459 (1.87)	6.028 (1.49)	6.619 (2.13)	6.258 (1.67)
CP2	5.297 (1.78)	4.815 (1.25)	5.392 (1.69)	5.149 (1.49)
TCP2	5.137 (1.51)	4.564 (1.12)	5.284 (1.75)	4.847 (1.38)
P3	6.446 (1.90)	5.821 (1.41)	6.302 (2.24)	5.450 (1.67)
PZ	6.820 (2.09)	6.305 (1.36)	7.420 (2.46)	7.024 (2.12)
P4	6.864 (2.68)	5.773 (1.10)	6.827 (2.44)	5.974 (2.01)
PO1	5.558 (1.72)	5.225 (1.12)	6.910 (2.64)	6.847 (2.60)
PO2	7.122(2.66)	6.492 (1.55)	7.574 (3.02)	7.284 (2.70)

EO = Eyes Open Baseline

MRT = Mental Rotation Test

Table A6.3 Summary of means and standard deviations of power in beta 2 frequency in good and poor imagers (VMIQ).

	Poor Imagers		Good Imagers	
	EO	MRT	EO	MRT
	Mean SD	Mean SD	Mean SD	Mean SD
F7	8.027 (1.63)	7.396 (2.31)	7.944 (3.13)	7.095 (1.69)
F3	7.829 (1.20)	7.256 (1.22)	8.137 (2.60)	7.434 (1.50)
FZ	6.047 (1.22)	5.854 (1.23)	6.036 (1.98)	5.853 (1.49)
F4	7.966 (1.27)	7.573 (1.81)	8.070 (2.25)	7.173 (1.68)
F8	6.510 (1.74)	5.514 (1.42)	6.268 (1.74)	5.522 (0.93)
TCP1	9.591 (5.53)	6.877 (1.44)	6.965 (2.40)	6.278 (1.60)
CP1	7.683 (1.45)	7.156 (1.18)	7.874 (2.66)	7.110 (1.46)
CP2	5.344 (1.32)	4.916 (1.08)	5.484 (1.76)	4.964 (1.30)
TCP2	7.257 (2.53)	6.247 (1.03)	6.337 (2.10)	5.616 (1.21)
P3	7.882 (1.94)	7.141 (1.10)	7.258 (2.59)	6.212 (1.38)
PZ	7.809 (1.52)	7.518 (1.37)	7.904 (2.56)	7.292 (1.32)
P4	7.821 (2.16)	7.040 (1.14)	7.356 (2.12)	6.401 (1.27)
PO1	7.295 (1.88)	6.741 (1.33)	7.509 (2.41)	7.093 (1.51)
PO2	9.065 (2.72)	8.237 (1.98)	9.406 (4.82)	7.911 (2.55)

Table A6.4 Summary of means and standard deviations of alpha power in good and poor imagers (MRT).

	Poor Imagers				Good Imagers			
	EO		MRT		EO		MRT	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
F7	7.383	(2.54)	7.448	(2.46)	9.402	(4.90)	8 773	(4.27)
F3	5.625	(1.25)	6.377	(0.91)	7.946	(4.29)	8.134	(3.73)
FZ	7.123	(1.76)	7.506	(1.67)	10.420	(4.65)	10.007	(4.82)
F4	6.912	(1.77)	6.369	(1.76)	10.115	(4.63)	9.185	(3.64)
F8	5.579	(2.01)	6.101	(1.65)	7.230	(2.90)	7.440	(2.49)
TCP1	7.230	(2.01)	6.815	(1.45)	11.206	(5.35)	10.109	(4.61)
CP1	8.052	(2.17)	7.847	(1.95)	14.475	(8.53)	12.249	(6.67)
CP2	7.252	(2.06)	7.169	(2.01)	12.666	(7.22)	10.519	(5.31)
TCP2	6.364	(2.04)	5.950	(1.78)	9.968	(4.31)	8.559	(3.84)
P3	7.990	(2.76)	7.045	(1.92)	11.793	(4.98)	9.514	(3.47)
PZ	8.196	(2.19)	8.083	(1.61)	14.884	(7.82)	12.610	(6.94)
P4	8.047	(2.16)	7.010	(1.45)	13.880	(6.64)	11.302	(5.31)
PO1	6.845	(2.46)	7.175	(1.32)	13.131	(6.20)	11.453	(5.53)
PO2	9.465	(3.90)	8.601	(1.51)	12.947	(6.48)	11.478	(6.75)

EO = Eyes Open Baseline

MRT = Mental Rotation Test

Table A6.5 Summary of means and standard deviations of beta 1 power in good and poor imagers (MRT).

	Poor Imagers		Good Imagers	
	EO	MRT	EO	MRT
	Mean SD	Mean SD	Mean SD	Mean SD
F7	5.058 (1.05)	4.869 (0.82)	5.068 (1.31)	4.945 (1.25)
F3	5.976 (1.51)	5.490 (1.22)	6.085 (2.10)	5.574 (1.72)
FZ	4.962 (0.10)	4.925 (1.15)	5.716 (2.12)	5.380 (1.66)
F4	5.583 (1.28)	4.881 (1.63)	6.023 (2.29)	5.522 (1.33)
F8	4.541 (1.23)	4.378 (1.10)	4.819 (1.48)	4.656 (0.90)
TCP1	6.281 (1.89)	5.667 (1.29)	6.046 (1.82)	5.454 (1.68)
CP1	6.238 (1.43)	6.148 (1.09)	6.989 (2.28)	6.241 (1.75)
CP2	5.066 (1.44)	4.955 (1.06)	5.718 (1.85)	5.071 (1.49)
TCP2	4.968 (1.47)	4.684 (0.98)	5.479 (1.53)	4.767 (1.23)
P3	6.242 (1.67)	5.540 (1.28)	6.601 (2.25)	5.740 (1.47)
PZ	6.584 (1.74)	6.407 (1.14)	7.691 (2.39)	6.911 (1.89)
P4	6.294 (1.95)	5.363 (0.95)	7.494 (2.74)	6.460 (1.63)
PO1	5.140 (1.27)	5.227 (1.18)	7.289 (2.40)	6.855 (2.40)
PO2	7.496 (3.02)	7.180 (1.61)	7.429 (2.50)	6.826 (2.50)

EO = Eyes Open Baseline

MRT = Mental Rotation Test

Table A6.6 Summary of means and standard deviations of beta 2 power in good and poor imagers (MRT).

	Poor Imagers		Good Imagers	
	EO Mean SD	MRT Mean SD	EO Mean SD	MRT Mean SD
F7	9.069 (2.19)	7.612 (2.35)	6.486 (1.40)	6.663 (1.27)
F3	8.460 (2.18)	7.460 (1.22)	7 713 (2.00)	7.408 (1.60)
FZ	5.892 (1.51)	5.803 (1.24)	6.392 (1.85)	6.179 (1.42)
F4	8.377 (2.07)	7.518 (2.19)	7.888 (1.66)	7.511 (1.24)
F8	6.347 (2.00)	5.145 (1.03)	6.368 (1.68)	5.825 (1.37)
TCP1	9.518 (5.91)	7.160 (1.35)	7.696 (2.43)	6.442 (1.37)
CP1	7.457 (1.84)	7.095 (1.05)	8.396 (2.43)	7.422 (1.51)
CP2	5.166 (1.48)	4.944 (1.09)	5.890 (1.63)	5.162 (1.26)
TCP2	7.078 (2.74)	6.375 (1.04)	6.763 (2.19)	5.797 (1.06)
P3	7.682 (2.11)	6.712 (1.30)	7.786 (2.62)	6.865 (1.39)
PZ	7.695 (1.86)	7.599 (1.37)	8.301 (2.39)	7.432 (1.35)
P4	7.366 (2.23)	6.640 (1.26)	8.048 (2.20)	7.079 (1.11)
PO1	6.698 (1.59)	6.626 (0.68)	8.286 (2.50)	7.429 (1.83)
PO2	10.223 (4.98)	8.876 (2.42)	8.786 (2.62)	7.796 (1.89)

EO = Eyes Open Baseline

MRT = Mental Rotation Test

Table A7.1 Summary of means and standard deviations of alpha power in good and poor imagers (VMIQ).

	Poor Imagers				Good Imagers			
	EC		1st P		3rd P		EC		1st P		3rd P	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
F7	8.17	(3.93)	7.59	(2.74)	7.69	(2.87)	10.85	(3.80)	10.81	(3.86)	10.53	(3.74)
F3	11.18	(6.97)	10.31	(4.53)	10.48	(4.49)	13.73	(4.46)	13.83	(5.02)	13.71	(5.04)
FZ	11.81	(7.35)	10.86	(5.17)	11.12	(5.06)	14.32	(4.63)	13.85	(4.99)	14.15	(4.95)
F4	11.03	(6.35)	10.19	(4.94)	10.07	(4.69)	13.20	(3.51)	13.09	(4.75)	13.14	(4.72)
F8	8.10	(4.16)	7.60	(3.24)	7.68	(3.13)	9.78	(2.47)	9.74	(2.79)	9.54	(2.51)
T5	12.66	(6.66)	12.91	(7.65)	13.03	(8.52)	16.52	(6.54)	15.54	(6.42)	15.95	(7.15)
P3	19.38	(12.1)	17.25	(13.8)	18.02	(15.6)	22.90	(10.5)	20.80	(11.3)	21.01	(11.2)
PZ	19.80	(13.7)	18.42	(15.8)	18.85	(15.1)	27.79	(12.1)	26.46	(13.2)	27.10	(13.3)
P4	22.42	(13.7)	19.77	(12.9)	22.30	(15.1)	25.00	(11.2)	23.03	(11.0)	23.10	(10.2)
T6	14.61	(6.2)	14.12	(7.4)	14.78	(7.5)	20.66	(9.8)	20.51	(10.7)	20.63	(10.5)
PO1	15.73	(11.1)	14.00	(10.1)	14.81	(9.9)	26.97	(13.5)	25.54	(14.4)	25.94	(14.1)
PO2	19.19	(10.3)	16.93	(10.1)	18.16	(10.9)	21.40	(9.1)	21.24	(11.8)	22.54	(12.9)
O1	13.50	(5.2)	12.45	(7.2)	12.44	(6.7)	20.14	(7.6)	19.54	(10.8)	20.24	(11.3)
OZ	14.09	(6.1)	13.26	(6.9)	13.19	(6.6)	19.61	(7.0)	19.04	(9.7)	20.06	(9.9)
O2	11.73	(5.5)	11.92	(7.9)	12.24	(7.6)	18.57	(7.2)	18.89	(9.7)	19.78	(10.0)

EC = Eyes Closed Baseline

1st P = First person Perspective

3rd P = Third person Perspective

Table A7.2 Summary of means and standard deviations of power in beta 1 frequency in good and poor imagers (VMIQ).

	Poor Imagers				Good Imagers			
	EC		1st P		3rd P		EC		1st P		3rd P	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
F7	5.44	(1.05)	5.04	(1.16)	5.23	(1.04)	5.44	(1.05)	5.04	(1.16)	4.99	(1.05)
F3	6.92	(1.42)	6.49	(1.60)	6.18	(1.45)	6.92	(1.42)	6.49	(1.60)	6.32	(1.50)
FZ	6.03	(2.02)	5.82	(1.85)	5.62	(1.64)	6.44	(1.29)	6.02	(1.42)	5.84	(1.36)
F4	6.86	(1.37)	6.71	(1.83)	5.68	(1.72)	6.86	(1.37)	6.71	(1.83)	6.45	(1.55)
F8	5.11	(1.22)	5.12	(0.98)	4.73	(1.28)	5.11	(1.22)	5.12	(0.98)	4.97	(0.83)
T5	7.12	(1.72)	7.11	(1.97)	6.68	(1.95)	6.99	(2.57)	6.93	(2.17)	6.91	(2.10)
P3	8.86	(3.26)	8.58	(3.56)	8.29	(3.65)	8.46	(3.16)	8.19	(2.86)	8.27	(2.97)
PZ	8.65	(3.28)	8.71	(3.73)	8.54	(4.15)	9.35	(2.84)	9.39	(3.53)	9.52	(3.43)
P4	9.43	(3.57)	9.17	(3.52)	9.50	(4.54)	8.44	(2.39)	8.32	(2.36)	8.27	(2.30)
T6	7.77	(2.29)	7.64	(2.54)	7.36	(2.47)	6.89	(2.09)	7.41	(2.23)	7.23	(2.12)
PO1	7.22	(2.68)	6.94	(2.76)	7.12	(3.03)	8.58	(3.04)	8.66	(3.68)	8.83	(3.83)
PO2	8.33	(2.49)	8.65	(3.12)	8.28	(3.18)	8.09	(1.91)	8.22	(2.52)	8.34	(2.71)
O1	6.93	(2.93)	6.48	(2.52)	6.04	(1.89)	6.71	(1.83)	6.81	(2.62)	6.92	(2.79)
OZ	7.13	(1.83)	7.65	(3.76)	6.98	(2.78)	6.86	(2.06)	6.87	(2.05)	6.96	(2.22)
O2	5.99	(1.85)	6.77	(4.27)	6.44	(3.61)	6.03	(1.68)	6.26	(2.07)	6.46	(2.17)

EC = Eyes Closed Baseline

1st P = First person Perspective

3rd P = Third person Perspective

Table A7.3 Summary of means and standard deviations of power in beta 2 frequency in good and poor imagers (VMIQ).

	Poor Imagers						Good Imagers					
	EC		1st P		3rd P		EC		1st P		3rd P	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
F7	6.69	(1.30)	8.54	(2.40)	7.78	(2.28)	6.52	(1.27)	6.82	(1.36)	6.71	(1.22)
F3	8.36	(1.63)	8.66	(1.99)	8.28	(1.25)	8.69	(2.06)	8.72	(2.26)	8.49	(2.30)
FZ	6.86	(1.62)	6.51	(1.53)	6.47	(1.31)	7.21	(1.53)	6.95	(1.96)	6.84	(2.06)
F4	8.54	(1.68)	8.46	(1.82)	8.08	(2.13)	8.74	(1.67)	8.89	(2.00)	8.67	(2.11)
F8	6.38	(1.95)	6.59	(2.42)	6.46	(2.53)	5.67	(0.85)	6.03	(1.09)	6.10	(1.02)
T5	7.76	(2.82)	7.90	(2.90)	7.45	(3.07)	6.69	(2.03)	7.44	(2.24)	7.21	(2.02)
P3	10.77	(2.84)	9.53	(2.45)	9.25	(2.26)	9.84	(3.30)	9.65	(3.57)	9.56	(3.55)
PZ	10.02	(2.62)	9.33	(2.50)	9.07	(2.48)	10.76	(3.37)	10.32	(3.37)	10.16	(3.28)
P4	10.30	(2.80)	9.62	(2.40)	9.78	(2.51)	9.72	(3.12)	9.22	(2.73)	8.89	(2.63)
T6	7.30	(1.96)	7.05	(1.75)	6.83	(1.92)	7.04	(2.01)	7.58	(2.14)	7.38	(2.30)
PO1	9.06	(2.70)	8.23	(2.08)	8.10	(1.89)	10.34	(3.94)	10.06	(4.16)	9.98	(4.33)
PO2	10.51	(2.34)	10.06	(2.99)	9.57	(2.33)	9.97	(3.11)	10.04	(3.53)	9.97	(3.55)
O1	10.40	(6.46)	8.83	(4.90)	8.05	(4.32)	8.75	(2.67)	9.14	(3.23)	9.05	(3.87)
OZ	10.41	(3.68)	10.45	(4.90)	9.49	(3.54)	9.03	(2.91)	9.15	(3.14)	9.16	(3.17)
O2	8.01	(3.13)	7.97	(4.05)	7.88	(3.52)	7.04	(2.56)	7.54	(3.12)	7.66	(3.45)

EC = Eyes Closed Baseline

1st P = First person Perspective

3rd P = Third person Perspective

Table A7.4 Summary of means and standard deviations of power in alpha frequency in good and poor imagers (MRT).

	Poor Imagers				Good Imagers			
	EC		1st P		3rd P		EC		1st P		3rd P	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
F7	7.31	(1.92)	9.00	(3.64)	6.97	(1.93)	11.71	(4.83)	9.37	(4.13)	11.16	(3.95)
F3	9.55	(2.69)	12.12	(5.30)	9.47	(3.08)	15.43	(7.35)	12.22	(5.42)	14.90	(5.49)
FZ	10.01	(3.02)	12.67	(5.94)	9.97	(3.32)	16.23	(7.56)	12.29	(5.10)	15.51	(5.59)
F4	9.63	(2.80)	11.75	(5.26)	8.89	(2.63)	14.65	(6.28)	11.85	(5.32)	14.50	(5.35)
F8	7.18	(2.28)	8.47	(3.65)	6.96	(2.23)	10.56	(3.95)	8.96	(3.02)	10.24	(2.81)
T5	12.11	(5.65)	14.65	(7.04)	12.47	(8.17)	16.77	(6.97)	13.56	(6.87)	16.07	(6.40)
P3	17.37	(9.66)	21.96	(14.3)	16.47	(14.9)	24.24	(13.4)	15.49	(10.0)	21.90	(11.6)
PZ	16.63	(7.32)	24.32	(18.1)	15.73	(10.1)	29.24	(15.4)	19.10	(10.5)	28.89	(15.1)
P4	19.15	(11.1)	22.33	(14.9)	18.51	(13.4)	27.48	(13.7)	19.59	(8.63)	26.57	(11.6)
T6	13.00	(4.67)	16.39	(10.8)	12.82	(6.71)	21.67	(9.88)	17.33	(8.22)	21.92	(9.34)
PO1	12.33	(6.31)	19.40	(15.2)	12.22	(6.15)	28.68	(14.0)	18.68	(11.6)	27.00	(13.2)
PO2	16.36	(5.75)	16.33	(9.61)	16.09	(8.37)	22.52	(11.5)	19.74	(10.5)	22.90	(12.9)
O1	21.46	(5.73)	17.05	(10.3)	20.77	(9.78)	11.27	(3.55)	13.79	(8.51)	10.69	(6.09)
OZ	12.06	(3.80)	13.63	(7.64)	11.93	(5.45)	20.75	(6.74)	17.50	(9.04)	20.18	(9.33)
O2	11.97	(4.42)	12.51	(8.77)	12.64	(6.79)	17.75	(8.73)	17.53	(9.71)	18.81	(11.2)

EC = Eyes Closed Baseline

1st P = First person Perspective

3rd P = Third person Perspective

Table A7.5 Summary of means and standard deviations of power in beta 1 frequency in good and poor imagers (MRT).

	Poor Imagers				Good Imagers			
	EC		1st P		3rd P		EC	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
F7	5.66(0.59)		5.23(0.42)		5.01(0.92)		5.35(1.38)	
F3	7.30(1.08)		7.01(0.69)		6.18(1.27)		6.70(1.74)	
FZ	6.67(2.04)		6.22(1.36)		6.14(1.55)		5.89(1.43)	
F4	7.30(1.13)		7.17(0.55)		5.72(1.71)		6.59(1.58)	
F8	5.67(1.37)		5.56(0.81)		4.55(1.08)		4.67(0.89)	
T5	7.34(2.14)		7.07(1.89)		7.01(1.90)		7.09(1.99)	
P3	8.95(3.11)		9.02(3.65)		8.35(2.65)		8.61(3.32)	
PZ	8.51(2.80)		9.70(4.14)		8.20(3.39)		9.58(3.24)	
P4	8.92(3.25)		8.85(3.23)		8.72(3.66)		9.28(2.98)	
T6	7.18(1.35)		7.22(2.05)		6.90(1.74)		7.72(2.73)	
PO1	6.52(2.18)		7.73(3.93)		6.59(2.22)		9.26(2.87)	
PO2	8.31(1.73)		8.52(2.68)		8.25(2.36)		8.33(2.44)	
O1	5.90(0.92)		5.93(1.66)		5.21(1.47)		7.75(2.86)	
OZ	6.24(1.31)		6.09(1.55)		6.59(2.90)		7.66(1.62)	
O2	5.88(1.64)		5.14(1.62)		6.77(3.81)		6.24(1.67)	

	1st P		3rd P	
	Mean	SD	Mean	SD
F7	5.03(1.54)		5.32(1.17)	
F3	6.24(2.00)		6.51(1.58)	
FZ	5.84(1.86)		5.49(1.34)	
F4	6.62(2.37)		6.60(1.51)	
F8	4.92(0.90)		5.30(0.97)	
T5	7.10(1.87)		6.67(1.82)	
P3	7.83(2.37)		8.21(3.70)	
PZ	8.37(2.78)		9.71(3.98)	
P4	8.75(2.73)		9.20(3.75)	
T6	7.98(2.38)		7.72 (2.45)	
PO1	7.69(2.24)		9.18(3.81)	
PO2	8.35(2.69)		8.28(3.13)	
O1	7.15(2.83)		7.45(2.27)	
OZ	8.45(3.64)		7.28(1.74)	
O2	8.02(4.05)		6.21(1.88)	

EC = Eyes Closed Baseline

1st P = First person Perspective

3rd P = Third person Perspective

Table A7.6 Summary of means and standard deviations of power in beta 2 frequency in good and poor imagers (MRT).

	Poor Imagers						Good Imagers					
	EC		1st P		3rd P		EC		1st P		3rd P	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
F7	6.35	(1.41)	8.46	(1.68)	7.28	(2.26)	6.99	(1.18)	7.30	(2.42)	7.30	(1.62)
F3	8.22	(2.16)	8.66	(1.25)	8.17	(1.83)	8.97	(1.58)	9.07	(2.79)	8.85	(1.93)
FZ	6.47	(1.55)	6.43	(1.28)	6.11	(1.43)	7.63	(1.53)	7.29	(2.15)	7.43	(1.86)
F4	8.31	(1.85)	8.57	(1.83)	7.57	(1.95)	9.15	(1.50	9.17	(1.98)	9.48	(1.96)
F8	5.77	(1.51)	6.43	(2.37)	5.34	(1.04)	6.42	(1.67)	6.58	(1.23)	7.54	(1.97)
T5	6.75	(1.90)	7.41	(1.91)	6.73	(2.09)	8.16	(2.82)	8.43	(3.03)	8.31	(2.91)
P3	10.09	(2.70)	9.91	(2.45)	8.96	(2.48)	10.90	(3.59)	9.68	(3.70)	10.14	(3.50)
PZ	9.34	(2.60)	10.11	(2.84)	8.59	(2.61)	11.60	(3.26)	9.81	(3.36)	10.83	(3.02)
P4	9.19	(2.81)	9.61	(2.44)	8.63	(2.54)	11.15	(3.05)	9.57	(2.87)	10.45	(2.45)
T6	6.71	(1.68)	7.09	(1.72)	6.27	(1.62)	7.85	(2.25)	7.74	(2.29)	8.20	(2.28)
PO1	11.72	(3.39)	9.64	(3.76)	10.80	(3.76)	7.80	(2.38)	8.90	(3.28)	7.52	(2.40)
PO2	10.12	(2.90)	10.84	(3.31)	9.74	(3.24)	10.74	(2.72)	9.70	(3.30)	10.23	(2.86)
O1	7.92	(2.25)	8.09	(1.97)	6.41	(1.99)	11.34	(6.60)	9.99	(5.69)	10.71	(4.89)
OZ	8.29	(2.19)	8.30	(2.23)	8.23	(3.19)	10.99	(3.77)	11.48	(5.25)	10.65	(3.34)
O2	7.07	(2.80)	6.69	(2.86)	7.64	(4.06)	8.18	(3.10)	9.05	(4.18)	8.33	(3.07)

Table A8.1 Experiment 3: Summary of means and standard deviations of power density in alpha frequency.

	EO		ACQ		NIM		REC	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
F7	1.094	(0.29)	1.105	(0.25)	1.123	(0.28)	1.152	(0.30)
F3	1.128	(0.33)	1.087	(0.31)	1.236	(0.45)	1.126	(0.45)
FZ	1.178	(0.35)	1.151	(0.35)	1.273	(0.50)	1.161	(0.41)
F4	1.175	(0.34)	1.128	(0.32)	1.262	(0.48)	1.140	(0.39)
F8	1.095	(0.26)	1.053	(0.21)	1.134	(0.32)	1.073	(0.26)
T5	2.259	(0.67)	2.183	(0.58)	2.445	(0.81)	2.445	(1.03)
P3	2.858	(0.78)	2.572	(0.84)	3.143	(1.16)	2.606	(0.90)
PZ	2.982	(0.70)	2.517	(0.63)	3.204	(1.13)	2.649	(0.77)
P4	3.022	(0.74)	2.940	(1.16)	3.658	(1.74)	3.026	(1.40)
T6	2.338	(0.62)	2.414	(0.59)	2.696	(1.01)	2.785	(1.37)
O1	2.726	(0.78)	3.036	(0.95)	2.975	(0.81)	2.764	(0.86)
OZ	2.449	(0.48)	2.770	(0.62)	2.864	(0.74)	2.633	(0.73)
O2	2.501	(0.58)	2.909	(0.93)	3.012	(1.02)	2.804	(1.09)
P3O1	2.792	(0.64)	2.804	(0.81)	3.059	(0.92)	2.685	(0.81)
P4O2	2.762	(0.57)	2.924	(0.85)	3.335	(1.27)	2.915	(1.11)

EO = Eyes Open

ACQ = Acquisition Trials

NIM = Novel Imaginary Movements

REC = Recall Trials

Table A8.2 Experiment 3: Summary of means and standard deviations of power density in beta 1 frequency.

	EO		ACQ		NIM		REC	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
F7	0.949	(0.51)	0.850	(0.31)	0.884	(0.38)	0.916	(0.31)
F3	0.740	(0.31)	0.685	(0.25)	0.767	(0.34)	0.760	(0.31)
FZ	0.612	(0.19)	0.602	(0.21)	0.646	(0.23)	0.606	(0.19)
F4	0.776	(0.35)	0.708	(0.28)	0.789	(0.33)	0.761	(0.32)
F8	0.898	(0.52)	0.828	(0.32)	0.875	(0.37)	0.893	(0.29)
T5	1.398	(0.43)	1.534	(0.47)	1.382	(0.39)	1.524	(0.56)
P3	1.392	(0.35)	1.412	(0.38)	1.395	(0.30)	1.385	(0.36)
PZ	1.349	(0.36)	1.347	(0.32)	1.348	(0.27)	1.329	(0.31)
P4	1.344	(0.29)	1.429	(0.33)	1.452	(0.32)	1.380	(0.32)
T6	1.311	(0.27)	1.554	(0.41)	1.406	(0.33)	1.444	(0.33)
O1	1.866	(0.76)	2.315	(1.09)	1.859	(0.56)	2.050	(0.90)
OZ	1.572	(0.39)	2.045	(0.86)	1.749	(0.62)	1.848	(0.68)
O2	1.573	(0.48)	2.188	(1.21)	1.893	(0.90)	1.981	(1.02)
P3O1	1.629	(0.51)	1.863	(0.70)	1.627	(0.38)	1.718	(0.59)
P4O2	1.459	(0.32)	1.808	(0.71)	1.673	(0.54)	1.681	(0.63)

Table A8.3 Experiment 3: Summary of means and standard deviations of power density in beta 2 frequency.

	EO		ACQ		NIM		REC	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
F7	0.835	(0.61)	0.774	(0.42)	0.946	(0.67)	0.920	(0.50)
F3	0.619	(0.52)	0.526	(0.27)	0.659	(0.56)	0.646	(0.44)
FZ	0.399	(0.18)	0.397	(0.16)	0.413	(0.19)	0.421	(0.19)
F4	0.686	(0.58)	0.576	(0.37)	0.678	(0.52)	0.664	(0.48)
F8	0.944	(0.86)	0.780	(0.49)	0.900	(0.69)	0.894	(0.54)
T5	1.007	(0.37)	1.283	(0.63)	0.986	(0.40)	1.206	(0.64)
P3	0.831	(0.28)	1.002	(0.37)	0.851	(0.23)	0.941	(0.36)
PZ	0.700	(0.19)	0.838	(0.27)	0.748	(0.21)	0.783	(0.25)
P4	0.736	(0.23)	0.912	(0.33)	0.841	(0.30)	0.855	(0.30)
T6	0.867	(0.23)	1.184	(0.49)	0.956	(0.34)	0.935	(0.26)
O1	1.650	(1.08)	2.232	(1.32)	1.671	(0.81)	1.947	(1.29)
OZ	1.273	(0.62)	1.833	(0.96)	1.505	(0.89)	1.640	(0.91)
O2	1.282	(0.67)	1.996	(1.32)	1.693	(1.24)	1.798	(1.23)
P3O1	1.240	(0.67)	1.617	(0.83)	1.260	(0.74)	1.444	(0.88)
P4O2	1.009	(0.40)	1.450	(0.80)	1.267	(0.74)	1.333	(0.74)

Table A8.4 Experiment 4: Summary of means and standard deviations of power density in alpha frequency.

	EC	ACQ	NIM	REC
	Mean SD	Mean SD	Mean SD	Mean SD
F7	1.397(0.50)	1.446(0.47)	1.441(0.40)	1.409(0.41)
F3	1.755(0.69)	1.667(0.58)	1.805(0.62)	1.673(0.59)
FZ	1.913(0.75)	1.845(0.59)	2.001(0.62)	1.908(0.66)
F4	1.771(0.63)	1.725(0.51)	1.846(0.53)	1.748(0.57)
F8	1.354(0.40)	1.356(0.34)	1.408(0.37)	1.371(0.33)
T5	4.446(1.94)	4.376(1.72)	4.331(1.87)	4.027(1.60)
P3	5.473(1.63)	5.328(1.96)	5.618(2.01)	5.103(1.74)
PZ	5.178(1.32)	5.120(1.62)	5.458(1.66)	4.991(1.43)
P4	6.327(2.15)	6.480(2.46)	6.567(2.41)	6.221(2.42)
T6	4.944(2.22)	5.040(2.02)	4.997(2.20)	4.652(1.99)
O1	5.612(2.51)	5.768(2.49)	5.359(2.52)	5.355(2.32)
OZ	4.975(1.99)	5.238(1.92)	5.009(2.08)	4.944(1.86)
O2	5.246(2.18)	5.713(1.99)	5.420(2.12)	5.442(1.97)
P3O1	5.402(1.97)	5.433(2.04)	5.240(1.95)	5.090(1.82)
P4O2	5.724(1.99)	6.053(1.99)	5.899(2.07)	5.776(1.98)

EC = Eyes Closed Baseline

ACQ = Acquisition

NIM = Novel imaginary Movement

REC = Recall

Table A8.5 Experiment 4: Summary of means and standard deviations of power density in beta 1 frequency.

	EC		ACQ		NIM		REC	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
F7	0.797	(0.21)	0.879	(0.56)	0.856	(0.52)	0.906	(0.57)
F3	0.849	(0.29)	0.811	(0.29)	0.832	(0.32)	0.804	(0.33)
FZ	0.828	(0.31)	0.799	(0.28)	0.831	(0.30)	0.687	(0.45)
F4	0.902	(0.45)	0.857	(0.34)	0.892	(0.40)	0.853	(0.38)
F8	0.845	(0.40)	0.827	(0.32)	0.833	(0.37)	0.806	(0.45)
T5	1.713	(0.46)	1.652	(0.52)	2.692	(1.58)	1.530	(0.40)
P3	1.901	(0.41)	1.789	(0.50)	1.864	(0.58)	1.678	(0.40)
PZ	1.780	(0.35)	1.675	(0.39)	1.703	(0.42)	1.584	(0.36)
P4	1.962	(0.48)	1.971	(0.55)	1.974	(0.56)	1.853	(0.49)
T6	1.788	(0.44)	1.923	(0.54)	1.769	(0.50)	2.951	(1.46)
O1	2.255	(0.85)	2.307	(0.84)	1.997	(0.64)	2.061	(0.50)
OZ	1.943	(0.50)	2.112	(0.60)	1.895	(0.57)	1.918	(0.50)
O2	1.974	(0.52)	2.353	(0.80)	2.119	(0.70)	2.184	(0.74)
P3O1	2.078	(0.55)	2.050	(0.58)	1.896	(0.54)	1.864	(0.39)
P4O2	1.961	(0.42)	2.147	(0.55)	2.012	(0.50)	2.016	(0.50)

EC = Eyes Closed Baseline

ACQ = Acquisition

NIM = Novel imaginary Movement

REC = Recall

Table A8.6 Experiment 4: Summary of means and standard deviations of power density in beta 2 frequency.

	EC		ACQ		NIM		REC	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
F7	0.618	(0.20)	0.737	(0.68)	0.725	(0.54)	0.732	(0.51)
F3	0.567	(0.33)	0.553	(0.28)	0.582	(0.39)	0.580	(0.38)
FZ	0.489	(0.23)	0.474	(0.21)	0.507	(0.26)	0.480	(0.24)
F4	0.646	(0.57)	0.615	(0.42)	0.656	(0.48)	0.637	(0.51)
F8	0.726	(0.44)	0.699	(0.35)	0.728	(0.45)	0.693	(0.42)
T5	1.000	(0.30)	1.046	(0.43)	0.908	(0.36)	0.963	(0.15)
P3	0.957	(0.23)	0.993	(0.28)	0.952	(0.28)	0.930	(0.26)
PZ	0.836	(0.17)	0.878	(0.24)	0.891	(0.25)	0.858	(0.24)
P4	0.904	(0.22)	1.010	(0.31)	1.001	(0.34)	0.977	(0.32)
T6	0.968	(0.21)	1.145	(0.39)	1.030	(0.32)	1.049	(0.30)
O1	1.658	(1.18)	1.819	(1.03)	1.504	(0.71)	1.508	(0.58)
OZ	1.283	(0.57)	1.634	(0.79)	1.449	(0.64)	1.399	(0.59)
O2	1.340	(0.58)	1.969	(1.07)	1.761	(0.93)	1.737	(0.92)
P3O1	1.320	(0.68)	1.428	(0.63)	1.234	(0.48)	1.229	(0.39)
P4O2	1.119	(0.36)	1.492	(0.64)	1.386	(0.60)	1.360	(0.56)

Table A8.7 Pearson correlations between frequency bands during Eyes Open

		Alpha	Beta 1	Beta 2
F7	Alpha	1.00		
	Beta 1	0.429	1.00	
	Beta 2	0.076	0.894***	1.00
F3	Alpha	1.00		
	Beta 1	0.677***	1.00	
	Beta 2	0.421	0.849***	1.00
Fz	Alpha	1.00		
	Beta 1	0.810***	1.00	
	Beta 2	0.600**	0.861***	1.00
F4	Alpha	1.00		
	Beta 1	0.608**	1.00	
	Beta 2	0.428*	0.929***	1.00
F8	Alpha	1.00		
	Beta 1	0.542**	1.00	
	Beta 2	0.432*	0.936***	1.00
T5	Alpha	1.00		
	Beta 1	0.655**	1.00	
	Beta 2	0.277	0.849***	1.00
P3	Alpha	1.00		
	Beta 1	0.578**	1.00	
	Beta 2	0.011	0.633**	1.00
Pz	Alpha	1.00		
	Beta 1	0.658***	1.00	
	Beta 2	0.070	0.488*	1.00
P4	Alpha	1.00		
	Beta 1	0.448*	1.00	
	Beta 2	-0.111	0.548**	1.00
T6	Alpha	1.00		
	Beta 1	0.389	1.00	
	Beta 2	-0.074	0.784***	1.00
O1	Alpha	1.00		
	Beta 1	0.800***	1.00	
	Beta 2	0.628**	0.928***	1.00
Oz	Alpha	1.00		
	Beta 1	0.614**	1.00	
	Beta 2	0.361	0.882***	1.00
O2	Alpha	1.00		
	Beta 1	0.619**	1.00	
	Beta 2	0.416	0.904***	1.00
P3O1	Alpha	1.00		
	Beta 1	0.611**	1.00	
	Beta 2	0.266	0.842***	1.00
P4O2	Alpha	1.00		
	Beta 1	0.416	1.00	
	Beta 2	0.063	0.762***	1.00

* $p < 0.05$

** $p < 0.01$

*** $p < 0.001$

Table A8.8 Pearson correlations between frequency bands during Acquisition

		Alpha	Beta 1	Beta 2
F7	Alpha	1.00		
	Beta 1	0.509**	1.00	
	Beta 2	0.160	0.851***	1.00
F3	Alpha	1.000		
	Beta 1	0.751***	1.00	
	Beta 2	0.403	0.815***	1.00
Fz	Alpha	1.00		
	Beta 1	0.823***	1.00	
	Beta 2	0.576**	0.859***	1.00
F4	Alpha	1.00		
	Beta 1	0.651***	1.00	
	Beta 2	0.384	0.881***	1.00
F8	Alpha	1.00		
	Beta 1	0.364	1.00	
	Beta 2	0.168	0.917***	1.00
T5	Alpha	1.00		
	Beta 1	0.646*	1.00	
	Beta 2	0.151	0.888***	1.00
P3	Alpha	1.00		
	Beta 1	0.631**	1.00	
	Beta 2	0.267	0.845***	1.00
Pz	Alpha	1.00		
	Beta 1	0.610**	1.00	
	Beta 2	0.160	0.676***	1.00
P4	Alpha	1.00		
	Beta 1	0.519**	1.00	
	Beta 2	-0.052	0.709***	1.00
T6	Alpha	1.00		
	Beta 1	0.530*	1.00	
	Beta 2	0.185	0.905***	1.00
O1	Alpha	1.00		
	Beta 1	0.788***	1.00	
	Beta 2	0.703***	0.965***	1.00
Oz	Alpha	1.00		
	Beta 1	0.668***	1.00	
	Beta 2	0.479*	0.950***	1.00
O2	Alpha	1.00		
	Beta 1	0.719***	1.00	
	Beta 2	0.522**	0.957***	1.00
P3O1	Alpha	1.00		
	Beta 1	0.654***	1.00	
	Beta 2	0.469*	0.950***	1.00
P4O2	Alpha	1.00		
	Beta 1	0.532**	1.00	
	Beta 2	0.236	0.922***	1.00

* $p < 0.05$

** $p < 0.01$

*** $p < 0.001$

Table A8.9 Pearson correlations between frequency bands during Mental Imagery

		Alpha	Beta 1	Beta 2
F7	Alpha	1.00		
	Beta 1	0.423	1.00	
	Beta 2	0.190	0.858***	1.00
F3	Alpha	1.00		
	Beta 1	0.728***	1.00	
	Beta 2	0.479*	0.881***	1.00
Fz	Alpha	1.00		
	Beta 1	0.831***	1.00	
	Beta 2	0.626**	0.871***	1.00
F4	Alpha	1.00		
	Beta 1	0.694***	1.00	
	Beta 2	0.456*	0.876***	1.00
F8	Alpha	1.00		
	Beta 1	0.455*	1.00	
	Beta 2	0.240	0.885***	1.00
T5	Alpha	1.00		
	Beta 1	0.495*	1.00	
	Beta 2	0.143	0.885***	1.00
P3	Alpha	1.00		
	Beta 1	0.642***	1.00	
	Beta 2	0.124	0.669***	1.00
Pz	Alpha	1.00		
	Beta 1	0.583**	1.00	
	Beta 2	0.180	0.633**	1.00
P4	Alpha	1.00		
	Beta 1	0.560**	1.00	
	Beta 2	0.047	0.740***	1.00
T6	Alpha	1.00		
	Beta 1	0.554**	1.00	
	Beta 2	0.195	0.843***	1.00
O1	Alpha	1.00		
	Beta 1	0.695***	1.00	
	Beta 2	0.526*	0.942***	1.00
Oz	Alpha	1.00		
	Beta 1	0.613**	1.00	
	Beta 2	0.439*	0.939***	1.00
O2	Alpha	1.00		
	Beta 1	0.666***	1.00	
	Beta 2	0.504*	0.957***	1.00
P3O1	Alpha	1.00		
	Beta 1	0.564**	1.00	
	Beta 2	0.239	0.873***	1.00
P4O2	Alpha	1.00		
	Beta 1	0.518**	1.00	
	Beta 2	0.261	0.932***	1.00

* $p < 0.05$

** $p < 0.01$

*** $p < 0.001$

Table A8.10 Pearson correlations between frequency bands during Recall

		Alpha	Beta 1	Beta 2
F7	Alpha	1.00		
	Beta 1	0.562**	1.00	
	Beta 2	0.259	0.846***	1.00
F3	Alpha	1.00		
	Beta 1	0.736***	1.00	
	Beta 2	0.593**	0.897***	1.00
Fz	Alpha	1.00		
	Beta 1	0.803***	1.00	
	Beta 2	0.591**	0.862***	1.00
F4	Alpha	1.00		
	Beta 1	0.756***	1.00	
	Beta 2	0.502	0.868***	1.00
F8	Alpha	1.00		
	Beta 1	0.561**	1.00	
	Beta 2	0.262	0.859***	1.00
T5	Alpha	1.00		
	Beta 1	0.457*	1.00	
	Beta 2	0.158	0.889***	1.00
P3	Alpha	1.00		
	Beta 1	0.679**	1.00	
	Beta 2	0.282	0.796***	1.00
Pz	Alpha	1.00		
	Beta 1	0.557*	1.00	
	Beta 2	0.167	0.710***	1.00
P4	Alpha	1.00		
	Beta 1	0.549*	1.00	
	Beta 2	0.081	0.773***	1.00
T6	Alpha	1.00		
	Beta 1	0.652	1.00	
	Beta 2	0.435	0.922***	1.00
O1	Alpha	1.00		
	Beta 1	0.802***	1.00	
	Beta 2	0.694***	0.969***	1.00
Oz	Alpha	1.00		
	Beta 1		1.00	
	Beta 2			1.00
O2	Alpha	1.00		
	Beta 1	0.732***	1.00	
	Beta 2	0.611***	0.956***	1.00
P3O1	Alpha	1.00		
	Beta 1	0.792***	1.00	
	Beta 2	0.652*	0.963***	1.00
P4O2	Alpha	1.00		
	Beta 1	0.626**	1.00	
	Beta 2	0.392	0.936***	1.00

* $p < 0.05$

** $p < 0.01$

*** $p < 0.001$

Table A9.1 Experiment 5: Summary of means and standard deviations of power density in alpha frequency.

	Eyes Open	Encoding	Control 1	Imagery	Control 2
F7	1.52(0.52)	1.46(0.43)	1.28(0.38)	1.49(0.39)	1.34(0.45)
F3	1.56(0.63)	1.40(0.51)	1.38(0.55)	1.40(0.47)	1.49(0.68)
Fz	1.48(0.68)	1.31(0.55)	1.26(0.52)	1.29(0.51)	1.35(0.67)
F4	1.48(0.61)	1.35(0.49)	1.33(0.49)	1.38(0.44)	1.41(0.60)
F8	1.28(0.38)	1.30(0.32)	1.19(0.27)	1.37(0.30)	1.30(0.37)
T5	2.77(1.01)	2.25(0.49)	2.19(0.53)	2.19(0.46)	2.33(0.71)
P3	2.83(1.25)	2.30(0.59)	2.30(0.68)	2.21(0.53)	2.28(0.65)
Pz	2.83(1.25)	2.41(0.76)	2.39(0.76)	2.27(0.57)	2.36(0.74)
P4	2.77(1.30)	2.36(0.81)	2.35(0.83)	2.25(0.65)	2.39(0.87)
T6	2.86(1.22)	2.37(0.74)	2.32(0.73)	2.28(0.69)	2.57(1.16)
O1	3.47(1.46)	2.94(0.70)	2.78(0.72)	2.81(0.66)	2.91(0.74)
Oz	3.37(1.48)	2.97(0.77)	2.80(0.80)	2.83(0.66)	2.84(0.73)
O2	3.48(1.47)	2.97(0.77)	2.84(0.78)	2.83(0.67)	2.98(0.81)
P3O1	3.15(1.34)	2.62(0.62)	2.54(0.68)	2.51(0.56)	2.59(0.69)
P4O2	3.12(1.37)	2.67(0.77)	2.60(0.79)	2.54(0.64)	2.69(0.83)

Table A9.2 Experiment 5: Summary of means and standard deviations of power density in beta 1 frequency.

	Eyes Open	Encoding	Control 1	Imagery	Control 2
F7	1.31(0.71)	1.25(0.66)	1.24(0.61)	1.27(0.61)	1.31(0.70)
F3	1.36(1.13)	1.43(1.08)	1.39(1.09)	1.46(1.00)	1.51(1.24)
Fz	0.82(0.34)	0.79(0.33)	0.76(0.31)	0.80(0.33)	0.82(0.42)
F4	1.13(0.76)	1.23(0.79)	1.25(0.87)	1.26(0.68)	1.31(0.92)
F8	1.04(0.56)	1.18(0.54)	1.15(0.54)	1.23(0.61)	1.38(0.76)
T5	1.38(0.36)	1.31(0.23)	1.29(0.27)	1.32(0.27)	1.35(0.30)
P3	1.42(0.38)	1.25(0.22)	1.21(0.24)	1.24(0.25)	1.31(0.33)
Pz	1.41(0.39)	1.22(0.26)	1.17(0.25)	1.17(0.23)	1.27(0.32)
P4	1.34(0.38)	1.21(0.25)	1.17(0.24)	1.18(0.23)	1.24(0.32)
T6	1.39(0.41)	1.33(0.29)	1.29(0.43)	1.29(0.29)	1.34(0.32)
O1	1.66(0.43)	1.61(0.28)	1.52(0.28)	1.59(0.33)	1.62(0.36)
Oz	1.65(0.44)	1.62(0.29)	1.49(0.28)	1.58(0.32)	1.58(0.35)
O2	1.65(0.43)	1.59(0.28)	1.48(0.26)	1.56(0.32)	1.57(0.34)
P3O1	1.54(0.40)	1.43(0.24)	1.36(0.26)	1.42(0.27)	1.43(0.24)
P4O2	1.50(0.41)	1.40(0.26)	1.32(0.25)	1.37(0.27)	1.41(0.32)

Table A9.3 Experiment 5: Summary of means and standard deviations of power density in beta 2 frequency.

	Eyes Open	Encoding	Control 1	Imagery	Control 2
F7	1.45(1.32)	1.52(1.18)	1.63(1.26)	1.39(1.03)	1.47(1.17)
F3	1.48(2.11)	1.60(1.60)	1.65(1.92)	1.44(1.56)	1.66(2.07)
Fz	0.54(0.34)	0.61(0.34)	0.6(0.40)	0.53(0.31)	0.60(0.50)
F4	0.99(1.18)	1.28(0.93)	1.18(1.03)	1.12(0.91)	1.26(1.22)
F8	1.09(0.98)	1.38(0.94)	1.37(0.95)	1.35(1.15)	1.55(1.25)
T5	0.82(0.31)	0.93(0.29)	0.88(0.30)	0.90(0.26)	0.90(0.30)
P3	0.79(0.26)	0.86(0.27)	0.80(0.24)	0.83(0.24)	0.83(0.29)
Pz	0.73(0.23)	0.78(0.25)	0.72(0.20)	0.77(0.22)	0.76(0.26)
P4	0.71(0.24)	0.77(0.23)	0.71(0.22)	0.75(0.22)	0.73(0.24)
T6	0.78(0.34)	0.89(0.32)	0.83(0.46)	0.86(0.28)	0.81(0.27)
O1	0.86(0.26)	1.01(0.28)	0.90(0.23)	0.10(0.30)	0.99(0.30)
Oz	0.85(0.27)	0.99(0.27)	0.88(0.24)	0.99(0.31)	0.97(0.30)
O2	0.86(0.28)	0.10(0.28)	0.88(0.27)	0.98(0.30)	0.95(0.31)
P3O1	0.83(0.25)	0.94(0.26)	0.85(0.23)	0.91(0.25)	0.91(0.29)
P4O2	0.79(0.25)	0.88(0.25)	0.80(0.24)	0.86(0.25)	0.84(0.27)

Table A9.4 Summary of means and Standard Deviations during the first three and last three trials of imaginary rehearsal

	Alpha		**Beta 1**		**Beta 2**	
Electrode	Trials A	Trials Z	Trials A	Trials Z	Trials A	Trials Z
F7	2.82(0.53)	2.53(0.47)	1.31(0.59)	1.25(0.68)	1.32(0.91)	1.47(1.17)
F3	2.59(0.54)	2.47(0.58)	1.42(0.98)	1.57(1.05)	1.34(1.42)	1.60(1.81)
Fz	2.83(0.58)	2.08(0.55)	0.79(0.36)	0.81(0.32)	0.50(0.28)	0.52(0.28)
F4	2.39(0.48)	2.02(0.49)	1.16(0.57)	1.35(0.84)	0.99(0.71)	1.18(0.97)
F8	1.95(0.32)	1.86(0.39)	1.22(0.57)	1.28(0.71)	1.27(1.05)	1.41(1.13)
T5	3.32(0.59)	3.66(0.55)	1.34 (0.28)	1.27(0.27)	0.90(0.22)	0.87(0.28)
P3	3.71(0.70)	2.84(0.48)	1.24(0.24)	1.19(0.26)	0.81(0.19)	0.81(0.24)
Pz	3.42(0.68)	3.04(0.56)	1.17(0.24)	1.13(0.25)	0.75(0.19)	0.76(0.23)
P4	3.50(0.67)	3.37(0.65)	1.18(0.26)	1.16(0.27)	0.72(0.1)	0.75(0.24)
T6	3.51(0.68)	3.72(0.76)	1.30(0.34)	1.27(0.30)	0.85(0.28)	0.85(0.28)
O1	4.16(0.78)	4.38(0.82)	1.61(0.37)	1.54(0.33)	0.98(0.29)	0.96(0.28)
Oz	4.30(0.81)	4.23(0.77)	1.60(0.38)	1.54(0.32)	0.97(0.31)	0.98(0.31)
O2	4.32(0.76)	4.33(0.77)	1.58(0.39)	1.53(0.33)	0.95(0.31)	0.98(0.31)
P3O1	3.64(0.72)	3.57(0.63)	1.42(0.28)	1.37(0.28)	0.90(0.22)	0.88(0.24)
P4O2	3.71(0.71)	3.62(0.68)	1.38(0.31)	1.34(0.28)	0.84(0.23)	0.87(0.27)

Appendix B

Modified Version of the Movement Imagery Questionniare

1. Starting Position: Make a fist with your right hand and then place it on your right shoulder so that your elbow is pointing directly in front of you.

   Action: Extend your elbow so that your hand leaves your shoulder and is straight in front of you parallel to the floor. Make sure that you keep your fist closed and make the movement slowly. Repeat 3 times.

   Mental Task: Assume the starting position. Form as clear and vivid a visual image as possible of the movement just performed. Do not perform the movement. Now rate the vividness of the image that was formed.

   Now attempt to feel your self making the movement just performed but without actually doing it. Rate the vividness of the sensation.

2. Starting Position: Stand with your feet and legs together and your arms at your side.

   Action: Raise your right knee as high as possible so that you are standing on your left leg with your right leg bent at the knee. Then lower your leg so that you are once again standing on two feet. Perform this action slowly. Repeat 3 times.

   Mental Task: Assume the starting position. Form as clear and vivid a visual image as possible of the movement just performed. Do not perform the movement. Now rate the vividness of the image that was formed.

   Now attempt to feel your self making the movement just performed but without actually doing it. Rate the vividness of the sensation.

3.	Starting Position	Stand with your feet slightly apart and your arms at your side.
	Action:	Bend down low and then jump straight up in the air as high as possible with both arms extended above your head. Land with your feet apart and lower your hands to your sides. Repeat 3 times.
	Mental Task:	Assume the starting position. Form as clear and vivid a visual image as possible of the movement just performed. Do not perform the movement. Now rate the vividness of the image that was formed. Now attempt to feel your self making the movement just performed but without actually doing it. Rate the vividness of the sensation.

4.	Starting Position	Stand with your feet slightly apart and your hands at your sides.
	Action:	Jump upwards and rotate your entire body to the left so that you land in the same position in which you started. That is, rotate to the left in a complete 360 degree circle. Repeat 3 times.
	Mental Task:	Assume the starting position. Form as clear and vivid a visual image as possible of the movement just performed. Do not perform the movement. Now rate the vividness of the image that was formed. Now attempt to feel your self making the movement just performed but without actually doing it. Rate the vividness of the sensation.
5.	Starting Position:	Extend your left hand straight out by your side so that it is parallel to the ground, palm down.
	Action:	Move your arm forward until it is directly in front of your body (still parallel to the ground). Keep your arm extended during the movement and make the movement slowly. Repeat 3 times.
	Mental Task:	Assume the starting position. Form as clear and vivid a visual image as possible of the movement just performed. Do not perform the movement. Now rate the vividness of the image that was formed. Now attempt to feel your self making the movement just performed but without actually doing it. Rate the vividness of the sensation.

6. Starting Position: Stand with your feet and legs together and your arms at your sides.

Action: Raise your left leg as high as possible keeping the leg extended, i.e. do not bend your knee. At the same time keep your right leg straight. Then lower your left leg so that you are once again standing on two feet. Perform these actions slowly. Repeat 3 times.

Mental Task: Assume the starting position. Form as clear and vivid a visual image as possible of the movement just performed. Do not perform the movement. Now rate the vividness of the image that was formed.

Now attempt to feel your self making the movement just performed but without actually doing it. Rate the vividness of the sensation.

7. Starting Position: Stand with your feet slightly apart and your arms fully extended above your head.

Action: Slowly bend forward at the waist and try and touch your toes with your fingertips. Then return to the starting position, with your arms extended above your head. Repeat 3 times.

Mental Task: Assume the starting position. Form as clear and vivid a visual image as possible of the movement just performed. Do not perform the movement. Now rate the vividness of the image that was formed.

Now attempt to feel your self making the movement just performed but without actually doing it. Rate the vividness of the sensation.

8. Starting Position: Make a fist with your right hand. Extend your hand above your head keeping your hand in a fist. Keep your other arm at your side.

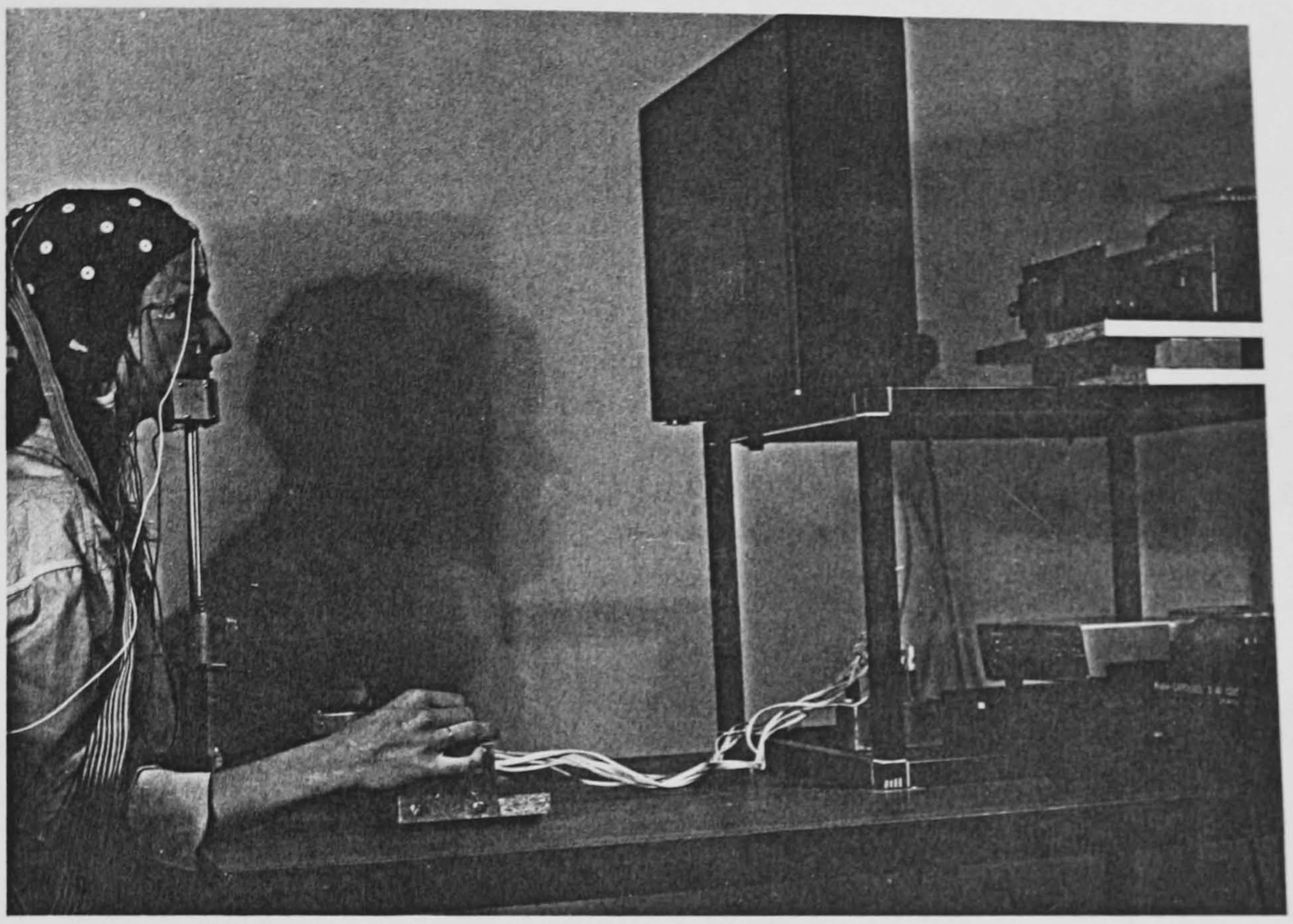
Action: Swing your extended arm straight down to your sides as rapidly as possible. Keep your arm straight and your fist clenched. Repeat 3 times.

Mental Task: Assume the starting position. Form as clear and vivid a visual image as possible of the movement just performed. Do not perform the movement. Now rate the vividness of the image that was formed.

Now attempt to feel your self making the movement just performed but without actually doing it. Rate the vividness of the sensation.

Appendix C

Figure C6.1 Experimental Set up in Experiment 1



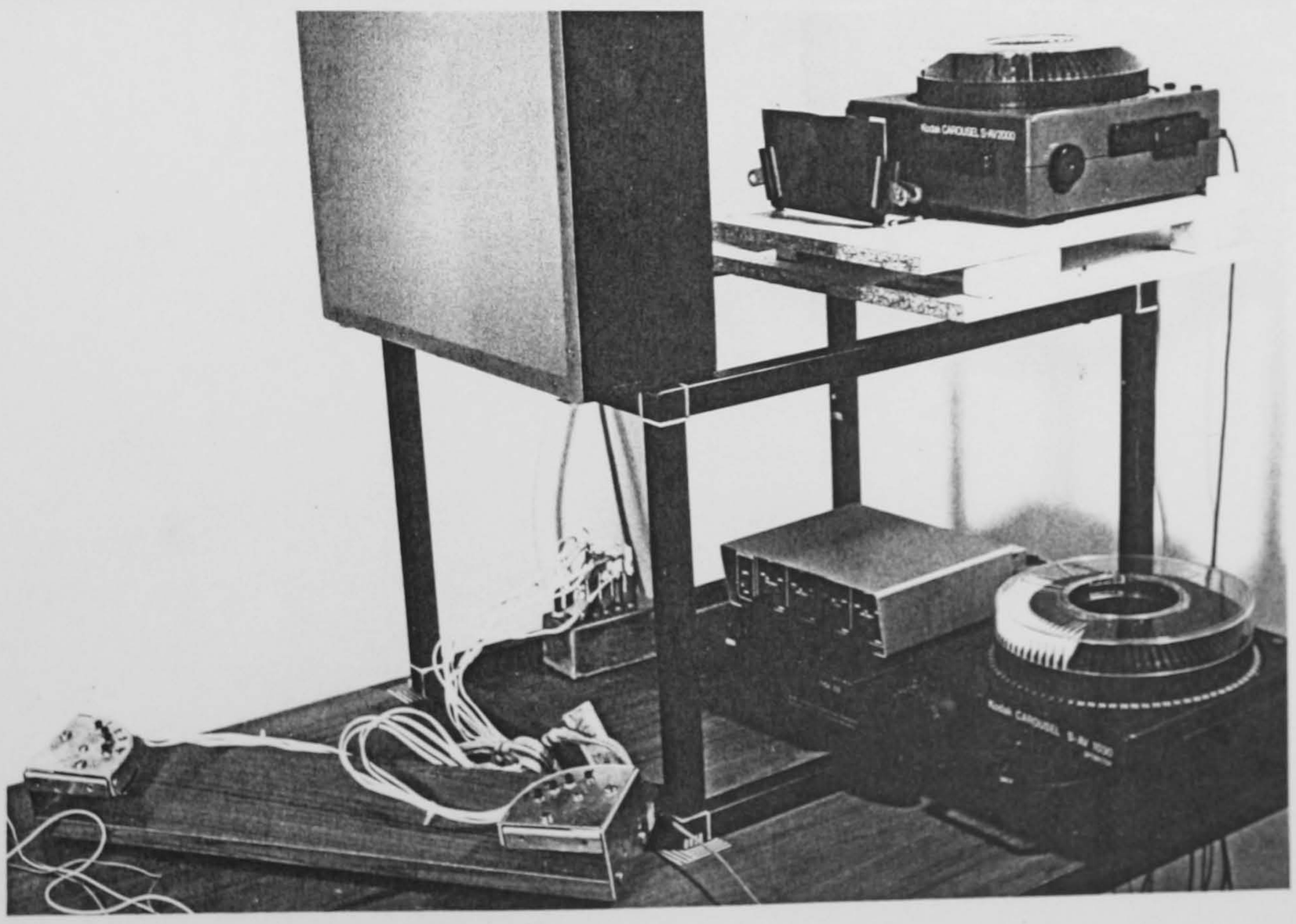


Figure C8.1 Experimental Set up in Experiment 3

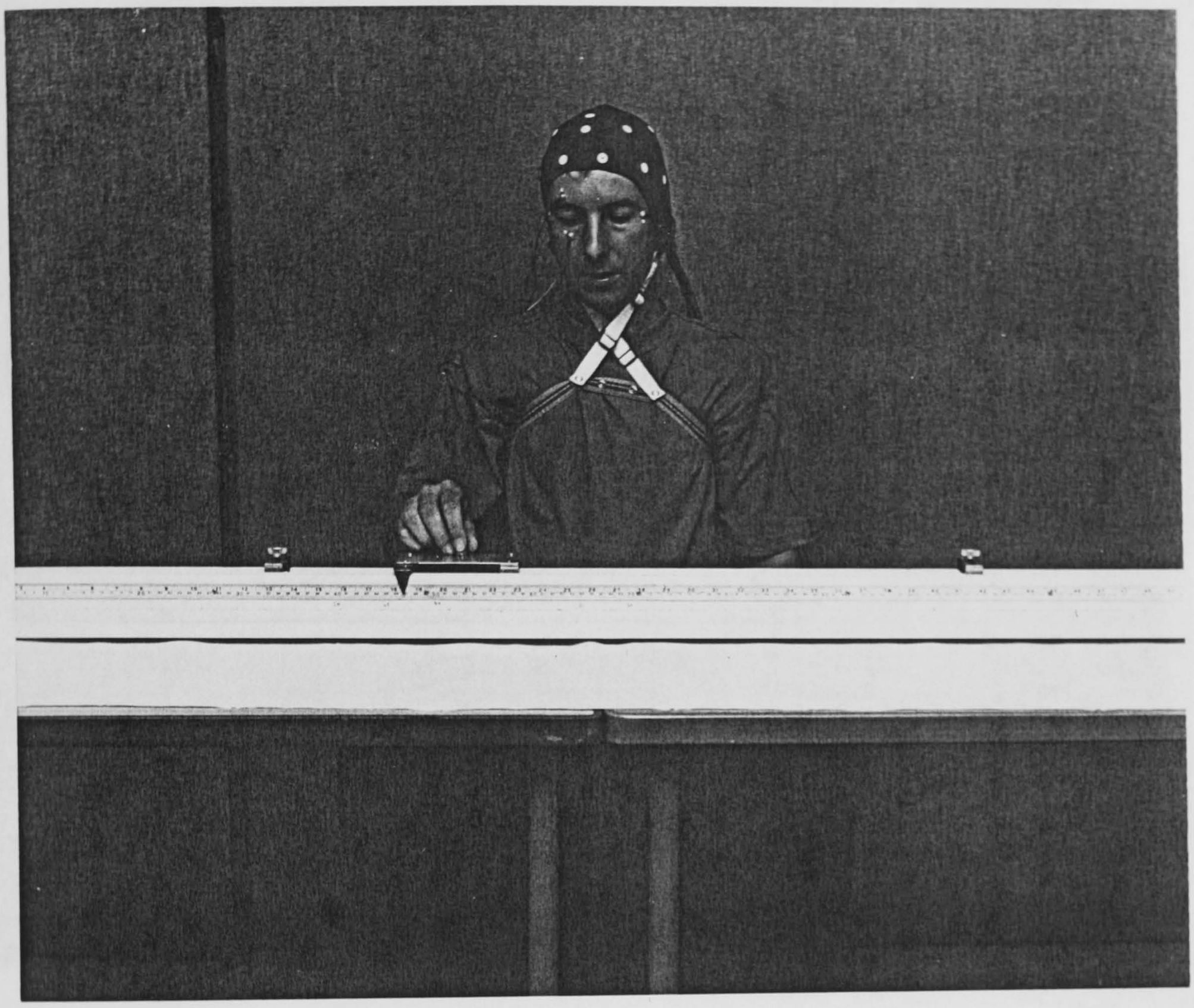


Figure C9.1 Experimental Set up in Experiment 5